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Energy efficient and reliable data gathering using internet of software-defined mobile sinks for WSNs-based smart grid applications

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ABSTRACT

The smart grid is an emerging concept that introduces innovative ways to handle the power quality and reliability issues for both service provider and consumers. The key aims of the smart grid (SG) in smart cities (SCs) is to preserve a certain level of residents' life quality and support the entire spectrum of their economic activities. In this paper, we present a novel Energy Efficient and Reliable Data Gathering Routing Protocol (ODGRP) for wireless sensor networks (WSNs)-based smart grid applications. The developed scheme employs a software-defined centralized controller and multiple mobile sinks for energy efficient and reliable data gathering from WSNs in the SG. The extensive simulation results conducted through the EstiNet 9.0 show that the designed scheme outperforms existing approaches and achieves its defined goals for event-driven applications in the SG.

1. Introduction

Nowadays, cities are facing overwhelming power supply and demands challenges to provide socio-economic sustainability and quality of life to its citizens [1–3]. On the other hand, the existing centralized controlled power grids (PGs) are facing several issues like low power quality, low customer satisfaction and too high electricity prices [4,5]. To this end, the existing centric approach-based power plants are not efficient enough to meet the demand of dynamic energy supply in the smart cities [6]. In this respect, the idea of smart grid is becoming more and more popular in international policies and scientific studies [7–10]. The smart grid using advanced information and communication technologies (ICTs) allow utilities to analyze, monitor and control power supply and demand with minimal impact on the environment in smart cities [11]. In smart grid, the Internet of Thing (IoT) technology has got a key role as it provides advanced connectivity between machines and humans for enabling a real-time transfer of knowledge between SG and SCs. Currently, wireless and wired communication technologies are used to collect information from different cyber-physical systems in the SG. However, compared to wired solutions, wireless communication technologies (WCTs) have a number of merits, including low-cost deployment, architecture flexibility, and long-distance communications [12]. In this context, the industrial wireless sensor network (IWSN) is a viable technology for various SG applications such as home energy management, distribution management, and several others.

In the smart grid, the integration of WSNs allows collecting information about the conditions of the cyber-physical systems (CPSs) for power generation, transmission and distribution in a reliable, efficient and cost-efficient manner. However, recent studies reveal that the W9 + s are facing unique challenges because of the distinctive SG environments, including high electromagnetic interference, system noise, and multi-path effects [13]. As a result, the performance of the quality of service-aware data gathering using WSNs is hampered in the SG. At the same time, the scalability and controllability due to hardware-centric networking approach are other challenges for WSNs in the smart grid. Over time, it is difficult to dynamically update WSNs settings with new features in an emergency scenario for efficient information collection in the smart grid [14]. This contributes to poor quality of service aware data collection in a real-time in the SG. To this end, the mobile sink (MS)-based data gathering in WSNs has drawn enormous attention in recent years in the SG. However, designing an efficient data collection path with dynamic sink mobility increases the network implementation complexity in the smart grid. To this end, the idea of software-defined sensor networking (SDN) offers improved network

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control and programmability by separating the control and data planes based on the vendor's application-specific devices in the smart grid. Thus, it significantly reduces the data plane dependence and improves the mobile sinks and sensor nodes (SNs) communication in the smart grid. However, the increase in routing table size for efficient and quick data gathering for the Internet of the software-defined sensor network brings excessive routing table management complexity in the smart grid [15]. Therefore, real-time control and managing dynamic power supply requirements is challenging in the smart grid.

This study aims to present a novel data gathering mechanism by using the Internet of SDMSs and WSNs for quality energy management in the SECs. In the designed scheme, a self-learning based controlled mobility patterns with predetermined trajectory is employed for gathering data in both active and passive manner in the SG. The mobile sinks by using a dynamic mobility pattern adjust their trajectory and speed for quality of service-aware data gathering in the smart grid. To provide real-time information, each mobile sink visits an assigned subnetwork most frequently in which events occurrence rate is high compared to other regions in the smart grid. The entire data is uploaded using short distance communication over high reliable communication links between SNs and MSs in the SG. Moreover, we also propose a geographical location based tree-based data forwarding mechanism to avoid long distance packets transmission of the faraway SNs in the SG. In the designed routing mechanism, each far away SN after receiving information relays data timely and accurate by dynamically adjusting its transmission power based on the sink trajectory in the network. Thus, the SNs are not required to upload their sensed information to an associated MS over long distance communication in the SG. Furthermore, in the proposed framework, the whole network computational burden is shifted on the centralized controller to avoid control message overheads. The simulations results obtained through the network simulation tool EstiNet 9.0 reveal that the designed scheme compared to existing studies significantly improves the ratio of data delivery and reduces the corrupted data packets, memory overflow, latency, and energy consumption to prolong the network lifetime (NLT).

The remainder of this work is structured as follow. The following Section 2 presents the literature review and problem statement, including existing studies, issues, and challenges. The proposed scheme, path loss, and energy consumption models are presented in Section 3 and Section 4, respectively. Section 5 presents simulation settings, metrics and discusses the performance analysis in detail. Finally, the summary of the research and solid potential research guidelines are given in conclusion Section 6.

2. Literature review

Presently, the aging PGs are being modernized to become SG for handling day-by-day growing energy demands in the smart cities. The smart grid needs to implement state-of-the-art diverse applications for providing low-cost and consistent energy supply benefits to consumers in the smart cities. Therefore, in the last few years, the energy efficient and QoS-aware routing in WSNs-based smart grid applications has got wide attention from the researchers. In the literature, a few routing schemes have been reported for reliable data delivery in WSNs-based SG application. Some authors try to solve network delay and packet delivery ratio in [16–19] while others try to address the problem of energy efficiency and packet error rates in [20–23]. In addition, some studies have focused on network stability [24], reliability [25] and throughput [26,27] in the smart grid. In these schemes, measurements and observed events are uploaded from SNs to the static sink. The single sink gathers data from SNs through multiple hops, which results in many-to-one communication in the network. This strategy of data transmission brings several problems. For example, the SNs near the sink deplete their energy faster as they are responsible to receive and forward an ample amount of information coming from the rest of the network. This non-uniform energy consumption among SNs in different regions decreases the overall NLT. As a result, SNs nearby the sink become non-operational and lead to the sinkhole or hotspot problem. Therefore, the coverage or connectivity of the WSNs cannot be guaranteed in the smart grid. Moreover, the high communications overhead in multi-hop information forwarding increases the interference and collisions, which results in the loss of data packets in the smart grid. Similarly, the increasing length of multi-hop routing paths due to an excessive number of hops decreases the probability of data success rate in the network. This results in low network throughput and high end-to-end delay in the network. Moreover, it also increases the data aggregation cost since it is proportional to the number of hops count between the source node and sink. On the contrary, the existing single MS-based schemes without modifications at the protocol stack level cannot be directly implemented in the SG.

To mitigate these problems, the MS has been introduced for collecting the generated data from static SNs by traveling around the network. For example, the work in [28] presents a novel mobile sink-based data gathering scheme for WSN applications. In the proposed scheme, initially an adaptive immune mechanism selects a set of cluster heads based on their high residual energy in different regions in the network. In the second phase, the adaptive immune mechanism controls and manages the MS movements in such a way that the overall control packets overhead are reduced during the data gathering process in the network. The proposed scheme performs well in low energy consumption and prolongs the lifetime of the network. However, the clustering mechanism performs poor in load balancing and the long distance communication between the cluster heads and the MS deplete their energy more quickly in the network. Moreover, the developed scheme requires excessive control message overheads during re-clustering in case of a cluster head failure and updating the location of the MS in the network. In addition, the high latency due to the poor trajectory of the MS is another issue. The authors in [29] try to solve the latency, energy consumption and trajectory issues between the MS and the rendezvous points (RPs) for reliable data gathering in the WSNs. The developed scheme employs *k*-means clustering and a weight function to select the cluster heads, i.e., RPs in such a way that the latency between the RPs and the MS is minimized in the network. The proposed scheme significantly reduces data gathering latency and energy consumption in the network. However, it faces the issues of poor synchronization between the RPs and the MS. Moreover, low speed of the MS increases the probability of memory overflow, particular for the rendezvous points away to the mobile sink.

Similarly, the study in [30] proposes a mobile sink-based data collection mechanism for WSNs. Initially, the entire sense filed is divided into different grid cells (GCs) and a head node for each GC is based on its high residual energy. The main purpose of these GC head nodes, it to share and update information with the neighboring GC heads, sensors, and MS. In this respect, each GC head periodically collects data from its member nodes and convey it directly or via neighboring heads to the MS. The designed scheme performs well in low energy consumption with higher packet delivery rates in the network. However, it faces several issues, such as packet collision due to flooding, mobile sink trajectory updating overheads, and memory overflow since the GCs are not visited frequently by the MS. To solve some of the issues mentioned above, the research in [31] presents a multi-mobile sinks-based data gathering protocol for WSNs-based SG applications. In the designed scheme, multiple MSs move in a strictly deterministic manner in different areas to improve region-based coverage issues, avoids nodes buffer overflow time and reduce latency by scheduling the mobile sinks movement in the network. The developed scheme reduces the total energy consumption and provides reliable data gathering for SG applications. However, the late arrival of the MS due to poor synchronization between the MS and the nodes increases the probability of packet loss, particularly for the sojourn nodes. Moreover, the failure of a single MS results in higher data gathering latency since it blocks the neighboring MSs in a specific region in the network. These issues can be solved by timely updating and control the MS trajectory, appropriate paths planning, and duty cycle for data gathering in the SG.

The MS mechanism achieves better resource optimization and routing compared to conventional local or distributed optimization schemes [32]. In this way, the mobile sink significantly balances the energy consumption by using short distance communication and prolongs the NLT. In addition, it also notably improves the data delivery rate over highly reliable links between SNs and MSs, which contributes to high network throughput in the network. Moreover, the mobile sink balances the traffic load among nodes, avoids data traffic congestion and even assists to gather data in the disconnected network. Furthermore, in several cases, the other functionalities like localization and coverage repair can also be achieved by using the mobile sink in the network. There are a few time-sensitive smart grid events monitoring applications in which data collection in a bounded time is required. In such applications, the use of a single MS increases the delay due to the low physical speed of the MS in a large-scale smart grid, which sometimes may result in sensors' buffer overflow. Therefore, the single MS-based data gathering schemes are not suitable since the observed sensor's information must be reported to the remote user within a given time limit.

To this end, a software-defined multi-mobile sinks based data gathering approach can significantly address these challenges. However, to find each mobile sink optimal trajectory and physical speed in order to gather QoS-aware data within a given time limit is challenging in the smart grid. The broadcasting of control packets to maintain the connectivity between sensors and mobile sink due to periodic sink location changing also consumes a significant amount of SNs energy, which decreases the NL in the SG. The other challenge is that each sensor nearer to the mobile sink consumes its energy quickly due to single-hop packets transmission in the SG. In addition, the data transmission using a single-hop communication from SNs away to the SDMSs also consumes a significant amount of energy, which is proportional to the transmission distance between sender and receiver SNs in the network. In this context, a tree-based multi-hop routing architecture can reduce the transmission energy consumption and also minimizes the network delay and balances the NLT in the smart grid. Motivated by aforesaid advantages and challenges, the main objective of this study is to design an opportunistic Internet of software-defined multi-mobile sinks-based data gathering mechanism for quality energy management in the smart cities. It should be noted that, we use the term mobile sink and software-defined mobile sink interchangeably in the rest of the paper. The working principle of our proposed data collection framework is explained in the following section.

3. Proposed Software-Defined Opportunistic Data Gathering Routing Protocol (ODGRP)

The entire working mechanism of the ODGRP is illustrated below.

3.1. Network model

In the proposed network model, the SNs, SDMSs and a base station (BS) are deployed for events monitoring purposes in a specific 2D region, i.e., a 320 kV smart grid as illustrated in Fig. 1. In Fig. 1, the car like icon indicates the mobile sinks each of them is embedded with OpenFlow switch and the pole like icon is the base station consists of a centralized SDN controller. The railroads indicate the mobile sink moving paths and the orange lines are hurdles generating the same interference level in the SG. The values of the interference level are defined in the path-loss model in Section 4. In addition, the computer, server, and solid black lines are the sensor nodes with a unique identity. The communication links between the user(s) and the BS, BS and MSs, and MSs and SNs are also presented by the black lines in the network. Consequently, the entire network consists of SNs and SDMSs are modeled as undirected graph $G = (V \cup \mathrm{MS}, E)$. In which E is the set of links between static SNs and MSs and V represents SNs in the SG. The randomly deployed static SNs based on their location are distributed into different subregions in the SG. Then, in a subregion suppose $G = (V, E)$ is a subnetwork in which E is the links between two SNs and V represents the set of SNs in the network. Therefore, the data generation rate of each SN deployed in a specific region could be different, however, it depends on events occurrence frequency in the network. The deployed SNs are same in terms of initial energy and data processing capabilities. The SNs and MSs are aware of their initial locations, which can be computed by using a localization mechanism presented in [33]. In addition, all the SNs have same sensing and communication radius, and communication is only successful if the neighboring SNs are within the transmission range that means there is a link between two SNs in the network.

Each mobile sink is embedded with an OpenFlow switch, and two wireless transmissions interfaces are installed for short and long distance communication between SNs and MSs, MS and neighboring MSs, and MS and BS in the network. The SDMSs are rich in computing resources and unlimited energy supply at the depot. Each mobile sink moves in the field periodically over a predefined roadmap with dynamic speed for gathering data according to the current status of the network. The paths on the defined roadmap are connected on which the mobile sinks can travel in the subregions and can stop at any point, which refers to a sojourn location on the roads in the network. We also assume that each mobile sink that completes its tour of data collection per round or runs out of energy must return to the depot for recharging or replacing the battery. It is also assumed that the SDN controller is embedded with the BS and is rich in memory, computing resources, and energy supply. The entire communication mechanism consists of three different layers. The first layer enables communication between SNs and MSs. In this layer, the deployed SNs observe the surrounding periodically, communicate with each other and send information to an associated parent sensor in a routing tree routed towards the rendezvous sensor node (RSN) or directly to the MS in the network.

The second layer allows communication between SDMSs and BS. In this layer, we assume one of the data transfer technologies such as 4G (Fourth Generation) or Microwave, which enables long-distance data transmission with high data rates between MSs and BS. Consequently, each MS compresses and forwards the received SNs information to the static BS via a third-party communication network. Finally, the third layer permits communication between BS and remote user(s) via Internet-of-Service (IoS) and IoT. To provide highly stable connectivity to the remote user(s), we assume long-distance data transfer technologies such as 5G (Fifth Generation) or Satellite communication because of their high data rates and coverage in the network. Thus, the entire collected sensory data is transferred to the remote user(s) of real-time control and monitoring operations for quality energy supply in the smart cities. In addition, by using advanced IoT technologies and services, the remote user(s) can also integrate a third-party network for remote data transfer, and thus has a global view of the whole smart grid. At first and second layers, we assume that the packet transmission delay of the MSs to BS and the BS to remote user(s) is negligible in the smart grid. Lastly, to avoid packet collision the transmitted signals from each SN and MS follows a carrier sense multiple access (CSMA) technique in the SG.

3.2. Software-defined routing architecture in ODGRP

The dynamic smart grid environments pose numerous challenges to transmission reliability of a multi-hop sensor network deployed for monitoring events in the network. This results in high energy consumption and poor data quality of the SNs in the SG. Therefore, designing a QoS-aware data collection scheme is challenging for providing a continuous and quality-aware power supply in smart cities. In the proposed scheme, the data and control planes are decoupled based on

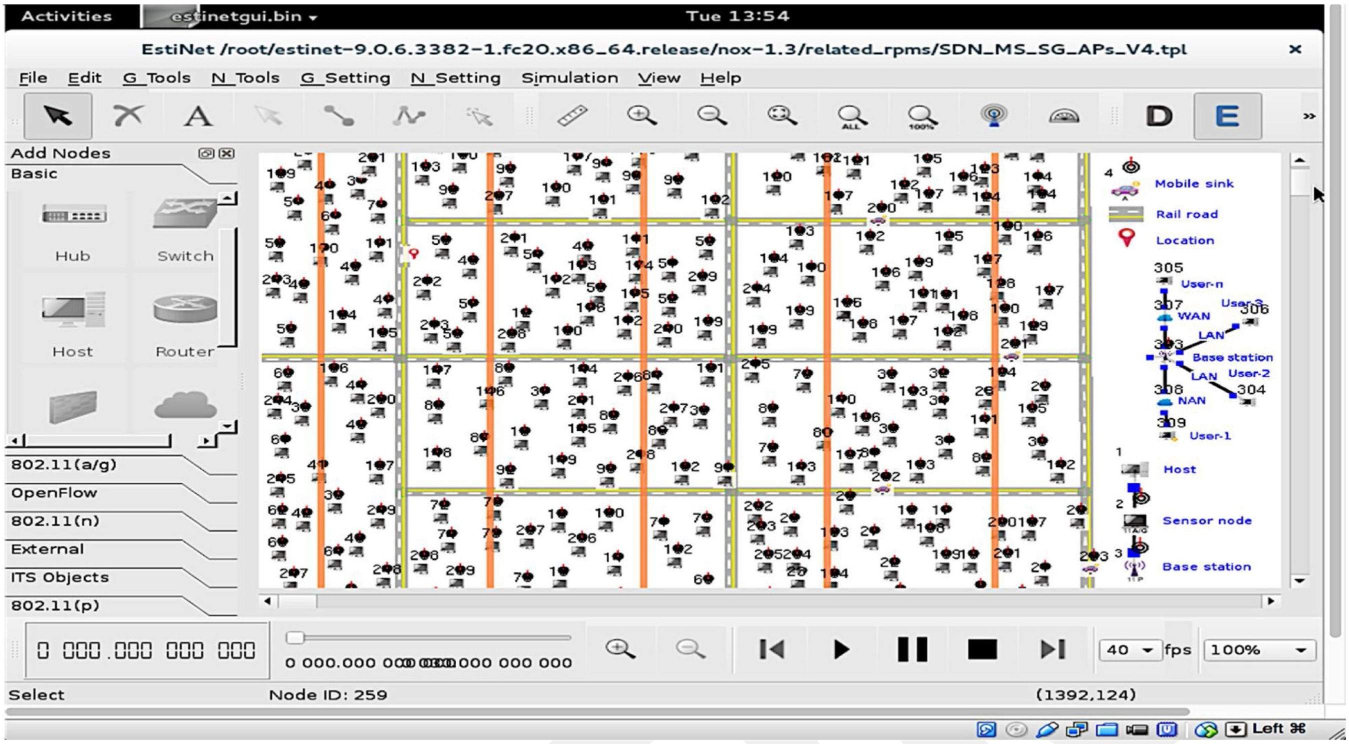


Fig. 1. Network model in ODGRP.

their functionality in the SG. The designed scheme significantly reduces SNs energy consumption and computational complexity by shifting the computational burden on the SDN controller in the SG. Thus, it reduces the overall events being handled in the SG. In addition, the information gathering over highly reliable communication links between RSNs and normal SNs designated by the SDN controller significantly increases the network throughput and packet delivery ratio with reduced corrupted data packets in the network. The whole software-defined networking architecture for MSs has been divided into two layers, namely; the control layer and the data layer in the smart grid. The control layer consists of a single centralized SDN controller aiming to perform necessary actions based on the user-defined rules in the smart grid. The SDN controller enables various smart grid events monitoring applications to run on top of it, which can be configured and modified in the network. The fundamental purpose of the SDN controller is to update network services and provide flow control messages to each switch embedded on the mobile sink. Thus, the use of a centralized SDN control enhances the efficient control of the MSs and sensor network as it provides a global view of the network.

The mobile sinks and sensor nodes are the key elements of the data plane as shown in Fig. 2. In the data plane, each mobile sink is embedded with a switch executing a software implemented OpenFlow protocol. The primary purpose of an OpenFlow protocol is to enable communication between the SDN controller and MSs in the smart grid environments. Thus, it provides a standardized way of communication between mobile sinks and the SDN controller by monitoring the topology in a real-time in the smart grid. The MS embedded with OpenFlow switch is comprised of a flow table (FT) that is represented by a triplet < header, counter, action >. In FT, the header matching pattern is used to identify the packets, the counter is an entry matching precedence, and the action function performs appropriate operations on the matched packet in the smart grid. The header pattern usually comprises of an input port number, unique identity number, source and destination address in the network. In the matching field, all packets according to the attributes belong to the same flow only if they match the same matching pattern in the network. The action field describes how the flow on each flow entry must process in a switch in the smart grid. The action field holds common operations such as modify the packet header, a specific output port, drop the packet, forward the packet and broadcast the packet in the network. In the actions field, usually, an action of a specified rule is applied to each packet of the corresponding flow in the smart grid. In a scenario, if multiple matching patterns match a packet then only the actions with the highest priority are applied to the SNs or MSs. Therefore, the list of defined rules is stored in an appropriate form with decreasing priority in the FT queue. This mechanism offers an instant reaction to the high priority rules so that halt and delay in the processing can be avoided in the network.

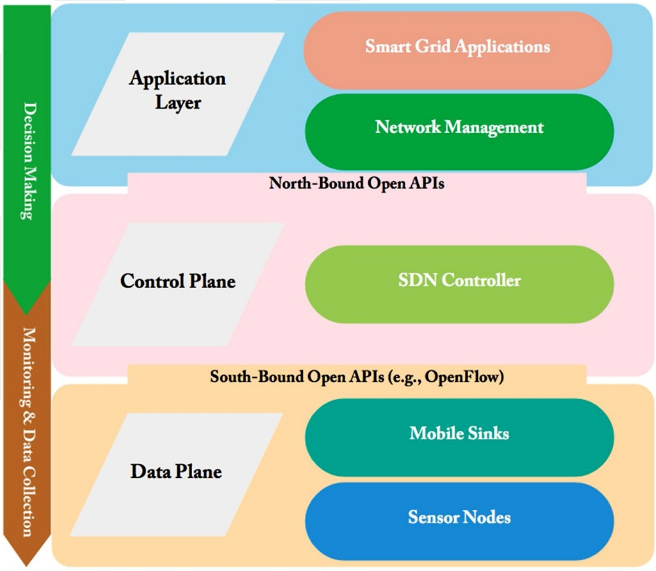


Fig. 2. A software-defined networking architecture in ODGRP.

Upon receiving a packet, each switch searches its header information in the FT. Then, it performs the related action only if a flow matches with an entry which is stored in the FT. Otherwise, the switch at first insert the packets into a temporary unresolved buffer queue and then forwards it to the SDN controller for appropriate rules or actions. Upon receiving the packet, the controller identifies the running smart grid application flow, defines appropriate actions and installing them on the associated switch flow table via an OpenFlow protocol. Thus, all control functionalities from the communication devices are extracted and placed in a logically centralized SDN controller, which helps the remote user(s) to change the network behavior and easily implement new actions according to the application requirements. In the proposed scheme, the whole working mechanism undergoes two phases. The first one is to select rendezvous points and set up routes for SNs in a way that meets application specific service guarantees in the SG. The second one is to collect data from SNs in both proactive and passive manner through the MSs in the network. Thus, the SDN controller is responsible to ensure that the traffic is routed over a feasible path between SNs and MSs under given QoS requirements in the SG. The entire process of route constructions and data gathering is divided into the following sections. Remember that, we use the terms switch embedded on the mobile, mobile switch and mobile sink alternatively in the following sections of this paper.

3.3. Multi-Mobile sinks path planning

Although the use of mobile sinks can significantly improve the quality of data collection in the SG, the key concern here is how to construct paths for mobile sinks so that quickly data can be collected from the entire network. The popular method in which a mobile sink can collect the sensed data from SNs by visiting them is known as the traveling salesman problem (TSP). The generalized form of the TSP is also known as the vehicle routing problem (VRP) used to find a set of optimal routes for multiple vehicles located at various locations in the network. The vehicle routing problem plans a set of approximately optimal routes for multiple mobile sinks in each specific region in the SG. Therefore, in the designed scheme, the paths planning problem is modeled as the VRP, which minimizes the distance traveled by all the mobile sinks in the SG as shown in Fig. 1. In sum, for each mobile sink embedded with a moving vehicle has four choices to move on the railroad like paths, including direction upside, downside, left side and right side in the smart grid.

3.4. Network initialization

The network initialization process basically uses a package of four types of messages, including initialization request (IREQ), neighboring discovery request (NDREQ), reply request (RREQ) and acknowledgment (ACK) in the SG. In the beginning, the SDN controller based on the user instructions sends an IREQ message to each mobile sink via an OpenFlow protocol in order to start an initialization process in the smart grid. After receiving the IREQ message, each mobile sink moves with constant speed along a pre-determined trajectory and broadcasts a network IREQ message by adjusting its radio communication range in a particular part of the network. The main purpose of the IREQ message is to allow SNs to compute the mobile sink trajectory and discover neighboring SNs in the network. Consequently, an IREQ message contains a mobile sink identity, location information, current speed, and time of packet transmission. The sensor nodes after receiving the messages synchronize their local time by using mobile sink time and locate the trajectory of the mobile sink. Then, each sensor node establishes its neighboring and MS trajectory table in the smart grid. To do so, each SN that receives the IREQ message from mobile sink starts negotiation with neighboring SNs by broadcasting an NDREQ message in its communication range in the smart grid. The NDREQ message contains the sensor's location, residual energy, angle information and unique identity information in the SG. If multiple NDREQ messages are broadcasted simultaneously by a large number of SNs then it may cause message conflict issues in the network.

To solve this problem, the SN accesses the vacant wireless channel by using the CSMA mechanism in the network. This mechanism decreases the number of packets colliding by avoiding the SNs to simultaneously access the wireless channels for sharing information in the network. A neighboring SN gets the NDREQ message stores the received information in its newly created neighboring discovery table and computes the distance and angle information to the sender SNs. This whole procedure repeats until each SN in the smart grid has most updated neighboring SNs information stored in its routing table. Later, each SN that received the NDREQ message sends an ACK message to the sender SN, which ensures the guaranteed delivery of the message. Later, each SN sends its neighboring discovery information towards the mobile sink by the RREQ message through multi-hops relay SNs in a greedy manner. The transmission process of neighboring discovery is completed as soon as the mobile sink receives the RREQ messages from all SNs located in a specific area in the SG. Finally, the received information from SNs is delivered to the SDN controller from MSs through an OpenFlow agent. Herein, it is also possible that the SN may receive multiple NDREQ messages from different mobile sinks in a region in the SG. In that case, a sensor replies to each mobile sink, and thus it can be associated with more than one MSs in the network. The whole network initialization process has been shown in detail from Figs. 3(a)–3(i) in the SG.

3.5. Rendezvous points selection and routing tree construction

In a large-scale smart grid, visiting every SN by the mobile sink is impractical since it experiences an excessive delay because of the longer path length and therefore may not be a good option for events driven applications. In this context, a potential solution is to find the minimum number of rendezvous points, i.e., sojourn locations in each region and permits each mobile sink to gather data from SNs at the rendezvous points only through short distance single-hop or multi-hop communication over highly reliable links in the SG. Therefore, in the proposed mechanism, a predefined number of sojourn locations based on the SNs position are selected in each subregion of the deployed network. Consequently, at this stage, the SDN controller has all the recent information about the MSs and SNs in the network. The SDN controller runs a package of rendezvous point's selection and shortest paths route construction algorithms from the source node towards the target SN in each subregion in the network. The entire process consists of three phases. In the first phase, the SDN controller computes the weight value of each SN based on its residual energy, link quality, location and the minimum distance between SNs and MSs in the smart grid. Then, it selects a set of a predefined number of one-hop SNs as rendezvous points or sojourn locations based on their maximum weight values in each subregion in the SG.

After choosing a set of RSNs, the SDN controller limited broadcasts a rendezvous appointment (RAREQ) request message, which floats through the associated mobile sink and delivers to each selected RSNs in the smart grid. In the proposed mechanism, the flooding of broadcast messages is avoided, as it would cause a broadcast storm, redundancy, signal collision, and severe interference issues in the network. These problems become more severe in a subregion where SNs are deployed densely. Therefore, the limited broadcasting to a set of specific RSNs reduces the problems such as interference, signal collision and redundancy in the network. After receiving the RAREQ message, each RSN replies via RREQ to the SDN controller through an associated mobile sink. The excessive number of sojourn positions may increase the waiting latency of the MSs for gathering data in the SG. Therefore, the proposed mechanism avoids an excessive number of SNs appointments as rendezvous points in each subregion in the smart grid. Now, each appointed RSN knows the associated mobile sink in the network. Consequently, each RSN and MS updates its location and neighboring information table in the smart grid. Upon receiving the RREQ message,

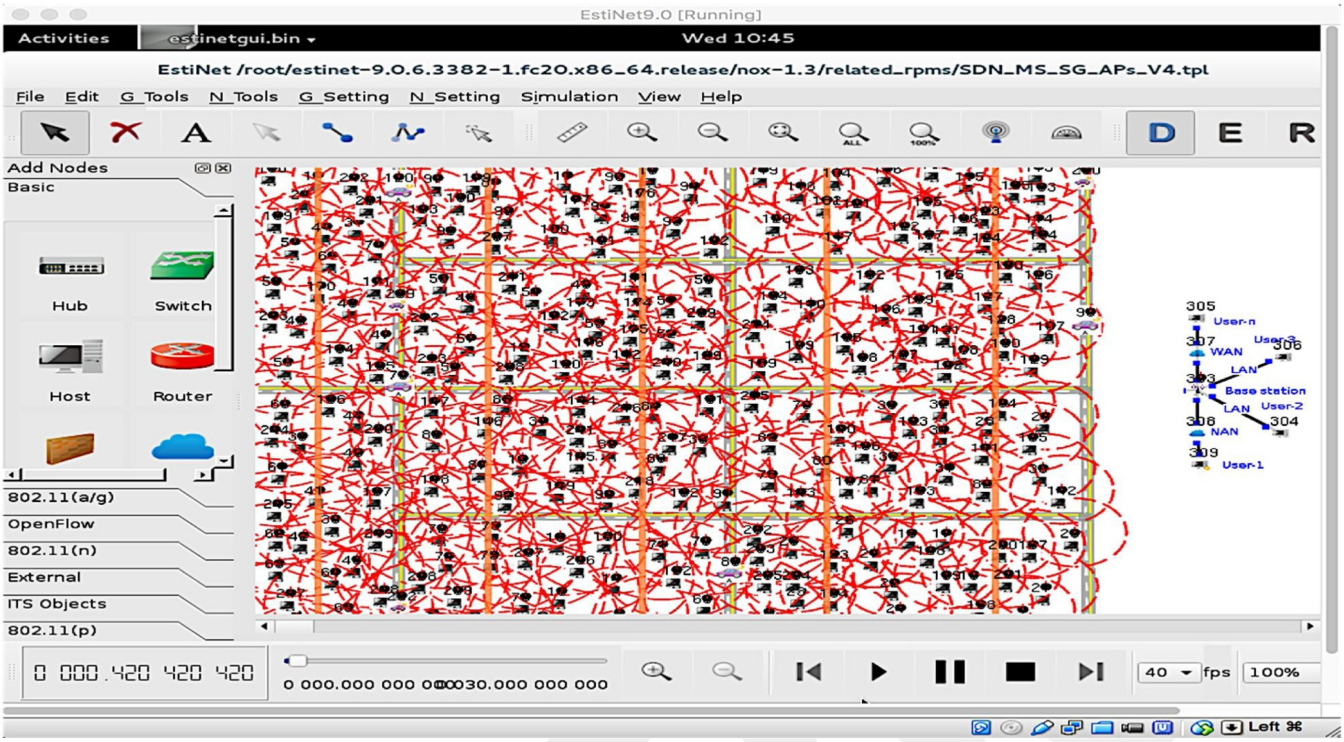
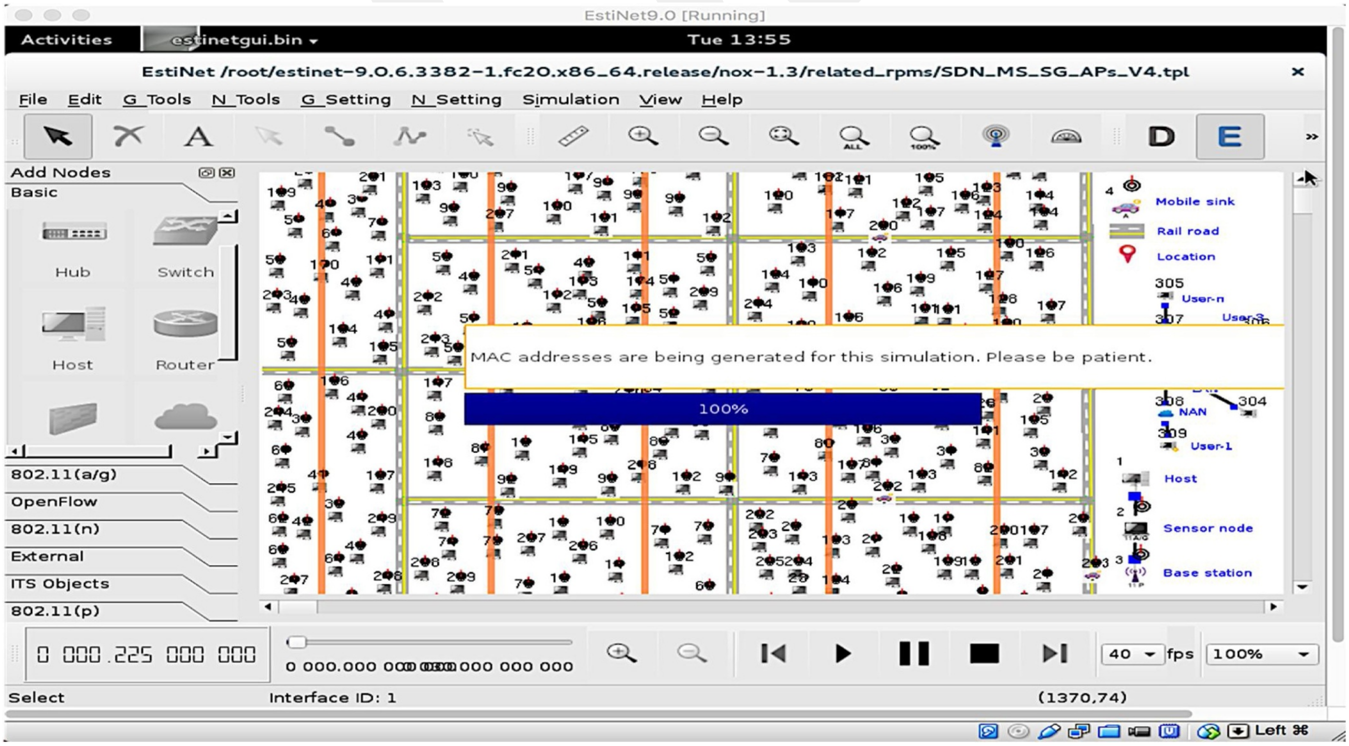


Fig. 3(a). The communication range of the SNs in the network.

the SDN controller defines data flow rules for each RSN and mobile sink. These rules and actions are forwarded through an OpenFlow agent to the associated mobile sink where they are saved in the flow table with decreasing priority.

In the second phase, a multi-hop routing architecture is constructed among RSNs in order to convey memory overflow or time critical data of the RSNs or normal SNs in the smart grid. The SDN controller computes the weight value of each RSN based on its residual energy, link quality, location and minimum distance information to its single hop neighboring RSNs in the smart grid. Then, it selects next hops RSNs based on their maximum weight values as relay RSNs in the direction of mobile sink's entering and leaving the field in the smart grid. After choosing a set of relay RSNs, the SDN controller limited broadcasts a relay appointment (REREQ) request message, which floats through the



MAC addresses are being generated for this simulation. Please be patient.

Fig. 3(b). Unique identity assignment process for each SN and MS in the network.

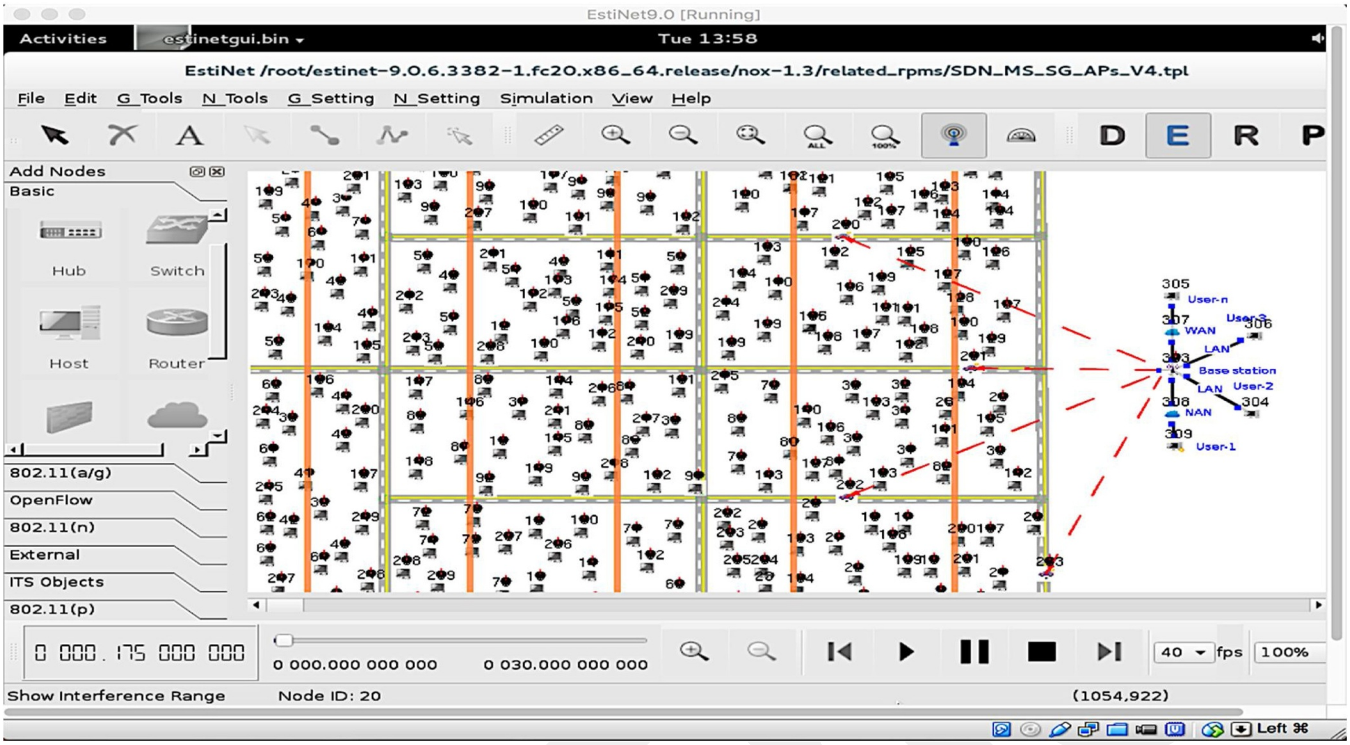


Fig. 3(c). A BS is broadcasting a network initialization message to each MS in the network.

associated MS and delivers to each selected relay RSN in the smart grid. Upon receiving the REREQ message, each RSN replies to neighboring relay RSNs and to the SDN controller through an ACK and REREQ message, respectively. At this stage, each relay RSN knows the neighboring relay RSNs in the subregion and updates its neighboring table in the network. Upon receiving the RREQ message, the SDN controller defines data flow rules for each relay RSN associated with the MSs. These rules and actions are forwarded through an OpenFlow agent to the associated MS where they are saved in the flow table of a switch with decreasing priority. The third phase starts as soon as the relay RSNs selection process ends.

In the third phase, a set of multi-hop tree like routing paths is constructed towards the rendezvous points in the network. The controller computes a predefined number of minimum spanning trees like

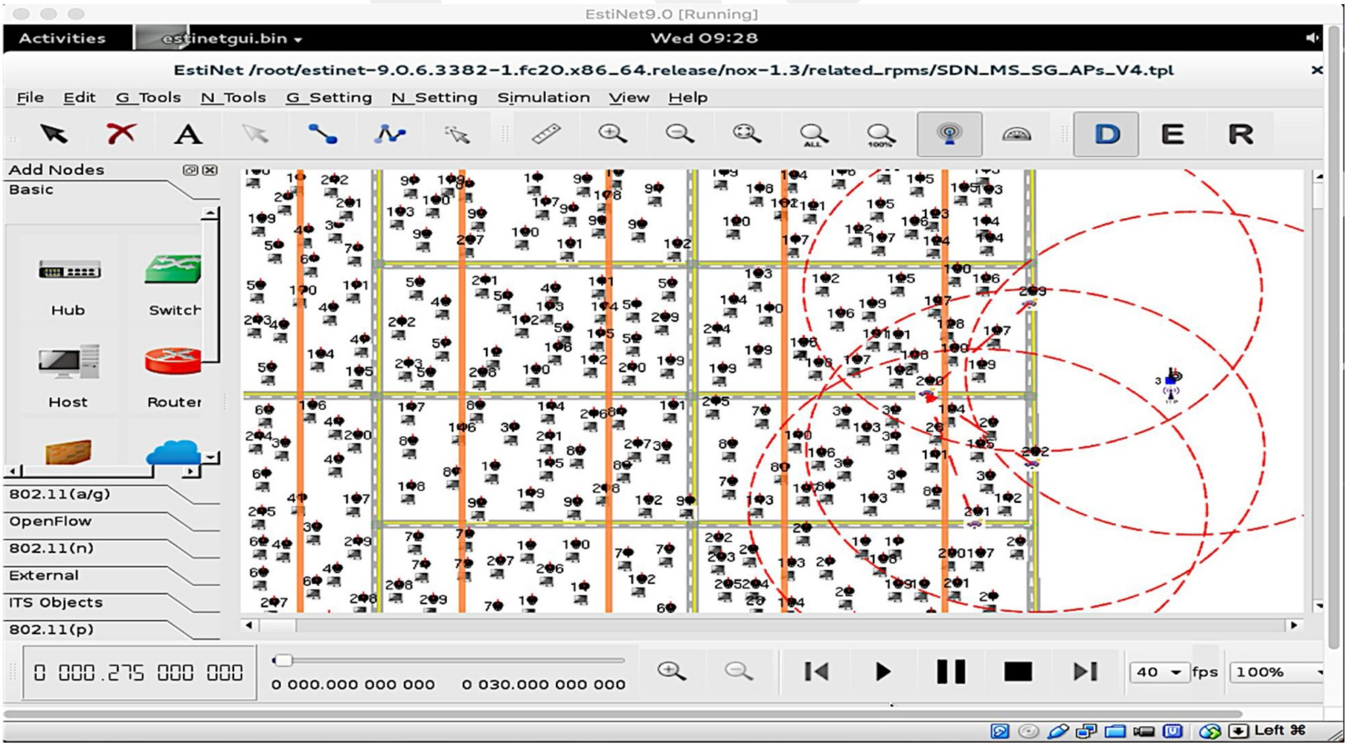
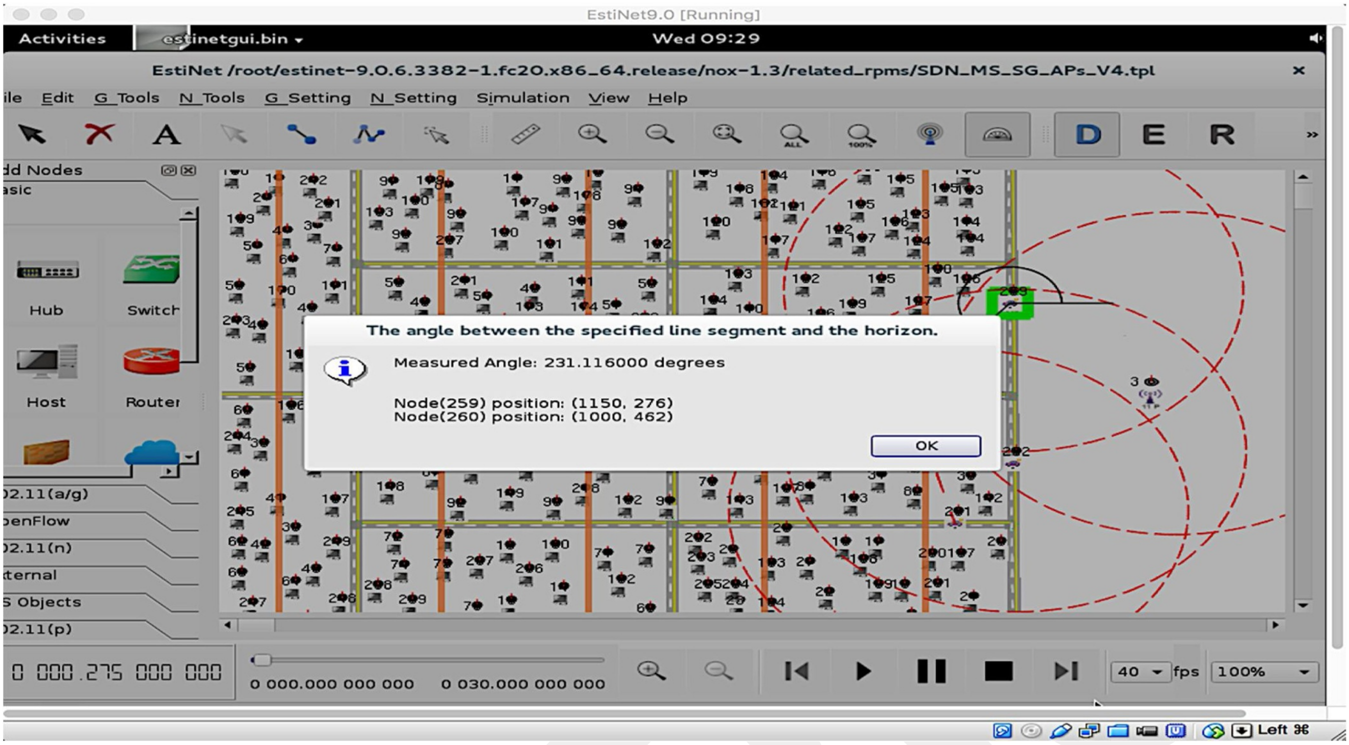


Fig. 3(d). After receiving a network initialization message from BS each MS is communicating with its neighboring MSs in the network.



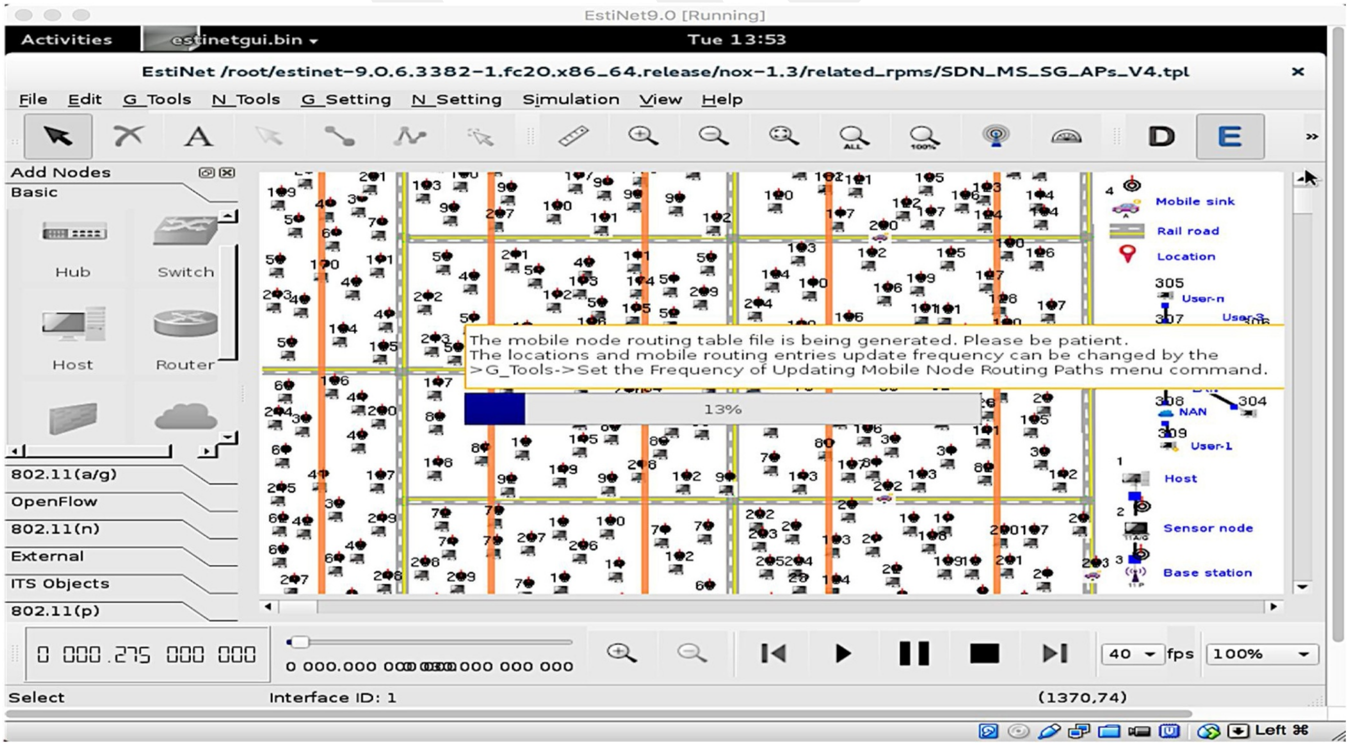
The angle between the specified line segment and the horizon.

Measured Angle: 231.116000 degrees

Node(259) position: (1150, 276)
Node(260) position: (1000, 462)

Fig. 3(e). Each MS is computing its angle information to the neighboring MSs in the network.

routing architecture in each subregion in the network. In the proposed scheme, a next hop relay SN is appointed by considering its maximum residual energy, link quality, minimum angle, and distance information in a greedy manner. The process continues until a predefined number of relay SNs are included in the selected routes in the SG. During this process, a specific identification number is assigned to each SN in decreasing order towards the associated rendezvous points. Thus, a set of a predefined number of minimum spanning trees like shortest path routing architecture is constructed towards the rendezvous points for uploading events data in the network. After computing the entire spanning trees in each subregion, the SDN controller sends a tree appointment request message (TRREQ), which floats through the associated mobile sink and delivers to each selected RSNs and normal SNs in the smart grid. Upon receiving the TRREQ message, each SN replies to



The mobile node routing table file is being generated. Please be patient.
The locations and mobile routing entries update frequency can be changed by the
>G_Tools->Set the Frequency of Updating Mobile Node Routing Paths menu command.

Fig. 3(f). Each MS is updating its routing table with the information of neighboring MSs in the network.

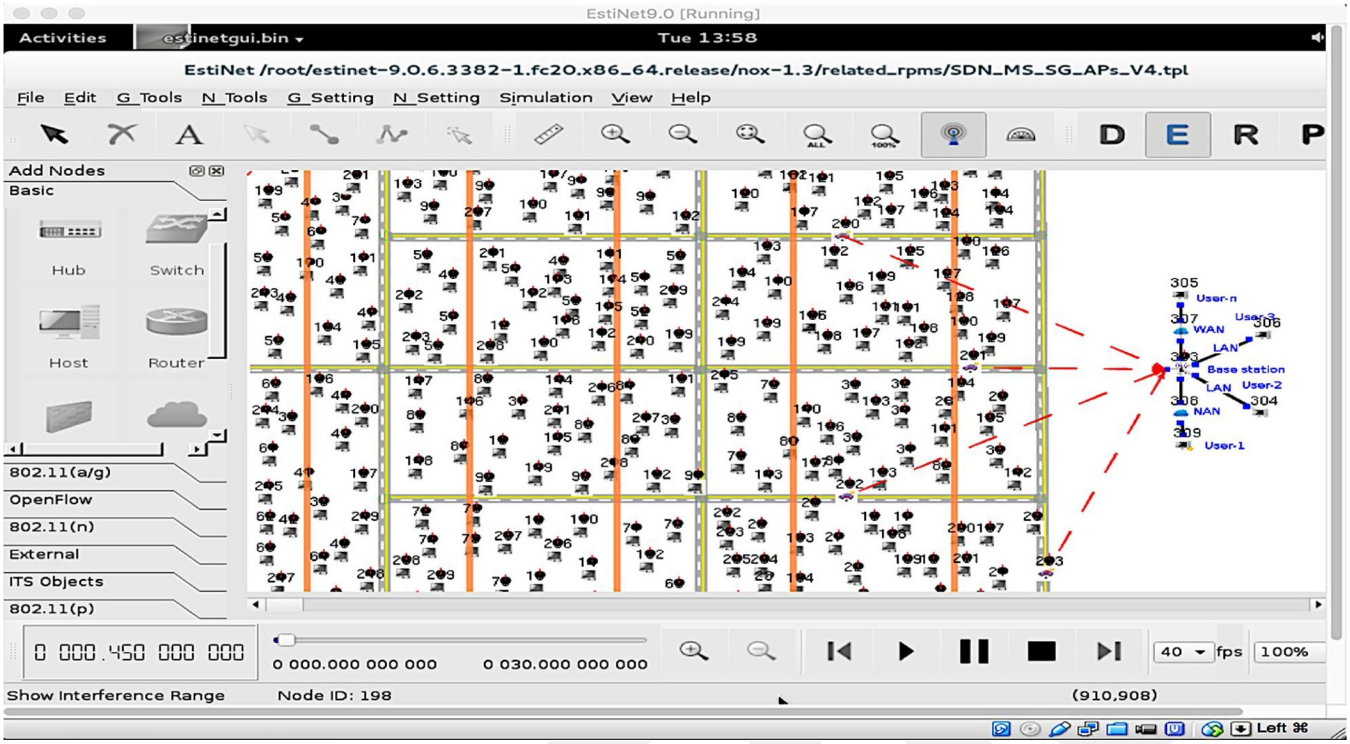


Fig. 3(g). Each MS after updating its routing table is sending information to the BS in the network.

its neighboring SNs by sending an ACK message, which floats towards the associated rendezvous point over a selected route in the network.

Consequently, each SN on receiving the ACK messages from neighboring SNs updates its routing table only if the entire about neighboring SNs already exist. Otherwise, it creates an entry and stores the recent information about the neighboring SNs in the routing table. Note that each normal SN requires two types of tables, namely routing table and neighbor information table. The routing table records relay SNs list with decreasing priority towards the associated RSN in the network. On the other hand, the neighboring list keeps the information of single-hop neighboring SNs in the network. Upon receiving the ACK message from neighboring SNs, the data flow rules are defined and stored in associated MSs switches with OpenFlow agents in the network. Thus, a set of parent-child and child-leaf like tree architecture

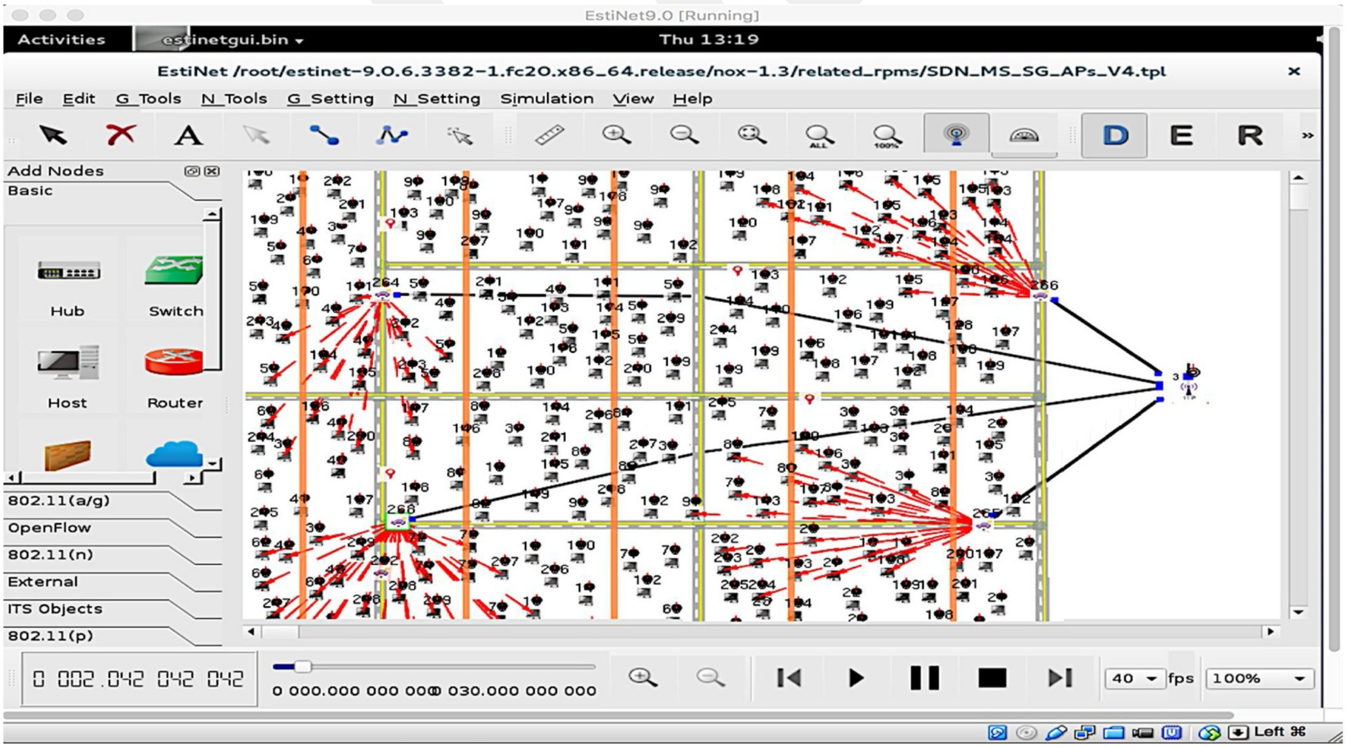
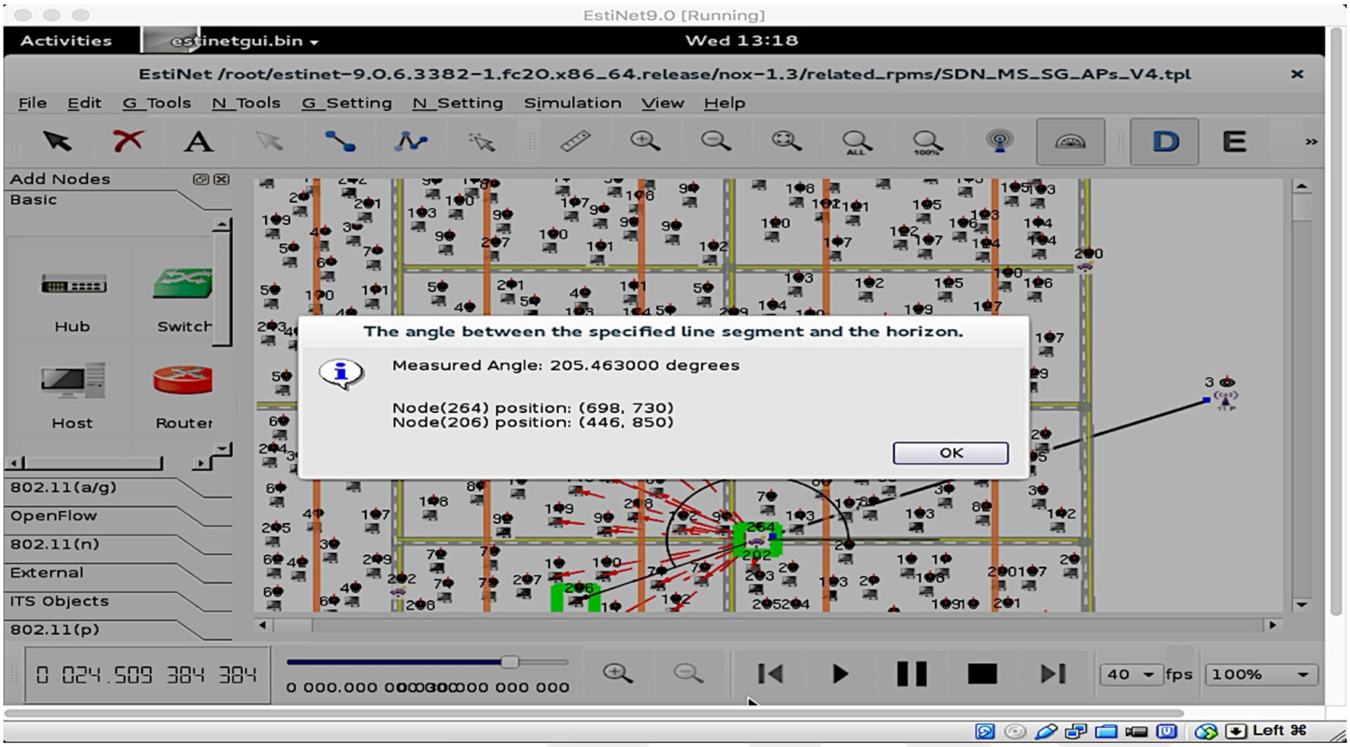


Fig. 3(h). Each MS is broadcasting a network initialization message to the SNs in the network.



The angle between the specified line segment and the horizon.

Measured Angle: 205.463000 degrees

Node(264) position: (698, 730)
Node(206) position: (446, 850)

Fig. 3(i). Each MS during sending a network initialization message is computing angle information of SNs for RSNs and routing tree construction in a particular region in the network.

from rendezvous points is constructed in which each child is tightly coupled with its parent in the network. In the proposed mechanism, a leaf node is the last node associated to the child node that usually contains high residual energy than other SNs in the network. The data collection process starts as soon as the routing tree construction process ends in the network.

3.6. Passive data gathering

The data collection process comprises of several rounds. In every data collection round, each SN monitors its vicinity and stores sensed information in the limited memory. In the beginning, the mobile sinks traverse with a constant speed and limited broadcast a polling (PREQ) request message to their associated SNs located in different regions in the smart grid. Upon receiving the PREQ message, each RSN computes the current location and distance of the MS in the SG. The RSNs continuously monitor the communication range of the MS and time when it enters and leaves the region. Thus, each RSN observes the mobile sink movement and updates its location table with the recent location information and time of staying in the communication range in the smart grid. Consequently, each SN after receiving the PREQ message starts to forward it's sensed data over a predefined route towards the rendezvous point in the SG. The SNs always add a unique timestamp on each data packet to record the effective time in the SG. Thus, the whole sensed information from the source node is routed over *K*-hop spanning tree towards the rendezvous points.

As soon as data is received, the RSN directly uploads sensed information to the mobile sink only if its communication range is higher than the measured distance to the mobile sink. The mobile sink stays for a predefined amount of time at each sojourn location for gathering data from RSNs and ensures that complete information has been transferred successfully. After gathering data, the flows are matched and appropriate actions are performed based on the rules defined in the OpenFlow switch. Then, the mobile after receiving the data from RSNs moves to another sojourn location in the network. During the data transmission process, each relay SN and MS after successfully receiving the packets replies via an ACK message in the network. After a predefined number of rounds, each mobile sink starts to moves based on its previous history information for events information collection in the SG. This self-learning based mobile sink movement extremely reduces the information collection latency in the SG. Thus, the complete information is uploaded to the mobile sinks in a predefined timespan in a real-time fashion in the SG. In this way, all the MSs visit the RSNs and complete their single data collection round.

3.7. Proactive data gathering

Generally, each SN in the SG monitors its surrounding and saves sensed information in the limited memory. However, in the highly dynamic smart grid environments, it is possible that the events occurrence rate in a region differs from other regions in the network. The SNs located in the high events occurrence regions face cache emergency issues due to always recording the events. In this scenario, the SN memory goes beyond the predefined threshold level, which results in the data packets loss of the critical events in the SG. In the proposed mechanism, the threshold value depends on the events occurrence rate and could be different in different regions in the SG. Consequently, the timely and accurate data forwarding from SNs to MSs is essential before the time deadline of the data packets expire. There are two solutions to this problem. One is to directly send data to the associated mobile sink via high transmission power. This is not a good choice since it consumes excessive node energy. The other solution is to send data over a minimum spanning tree towards the RSNs in a greedy manner. In this scenario, the SN near to overflow its memory sends a cache emergence (CEREQ) message request to the associated rendezvous sensor directly or over a predefined data route in the SG. If the RSN is currently available then it forwards an RREQ message to the cache emergency sensor directly or over a predefined route in the network. At the same time, the RSN based on its previous history starts to locate the mobile sink trajectory in the SG.

Consequently, there are two possibilities here either the mobile sink will arrive or already has visited the RSN for data collection in the network. The information of the mobile sink location is obtained based on the arrival and departure information saved in the location table of every rendezvous sensor in a greedy manner. Consequently, a rendezvous SN based on its previous mobile sink history information starts negotiating with its neighboring RSNs in order to convey messages to the mobile sink. As soon as, the cache emergency SNs send their sensed data to their associated RSNs in the smart grid. The RSNs after receiving the data, regardless of the mobile sink has not yet reached, send the received information towards the neighboring RSNs in the direction of the mobile sink. Then, each receiving RSN forwards the message again to the nearest rendezvous sensor that is more nearer to the MS. This process repeats until the data is delivered to the associated mobile sink in a greedy manner. Thus, the complete information is uploaded to the closest MS in a proactive manner. Similarly, if the cache emergence occurs at the RSN then it also sends its data to neighboring RSNs towards the MS regardless of it has yet reached or not. Otherwise, it uploads the information directly to the MS in a case if the MS is in the communication range. Thus, the designed scheme reduces the data loss rate by avoiding excessive sensor's memory overflow problems in the network. Similarly, the time emergency data from SNs or RSNs is uploaded towards the mobile sink before the packets deadline expires. Throughout the data forwarding process, each sender SN or RSN receives the ACK messages from data receiving SNs or RSNs in the SG.

3.8. Rendezvous points and routing tree reconstruction

The energy of RSNs is exhausted prematurely due to relaying a huge volume of neighboring SNs information in the SG. Therefore, it is important that an RSN goes beyond the predefined threshold energy limit must be replaced with the new one in order to balance the energy consumption load in the network. To do so, if the energy level of an RSN becomes lower than the defined threshold energy level then it sends a low energy (LEREQ) message to the associated mobile sink. Upon receiving the LEREQ message, the flow of the RSN is identified in the switch and is forwarded to the SDN controller via an OpenFlow agent. As soon as the LEREQ message is delivered, the control appoints a new RSN based on its high weight since it already has recent information of the RSNs in the network. Herein, it is also possible that more than one SN have the same weight value in a subregion in the network. In that case, an RSN is appointed opportunistically in a subregion in the SG. After selection, the rendezvous point appointment (RAREQ) message is forwarded to the switch and delivered to the new RSN in the network. Upon receiving the RAREQ message, the new RSN sends an ACK message to the associated mobile sink. After receiving the ACK message, the rules and necessary actions are defined by the SDN controller and stored in the corresponding switch FT with decreasing priority. This periodic rotation of the RSNs balances the energy consumption load, which results in a longer NLT in the SG.

After a new RSN selection, the process of tree-like routing path selection starts in a subregion in the SG. The SDN controller computes the next hop relay SN and appoints based on its high weight value towards the RSN in the network. This process repeats at each hop until a minimum spanning tree like routing path with maximum five sensors is constructed in the network. Then, the SDN controller sends a limited broadcast TRREQ message to the associated MS, which is forwarded and delivered to a particular RSN and normal SNs in the network. The TRREQ message contains all SNs information along the defined routes in the network. The new information is saved and previous old history is removed from the sensor's history table in the SG. Herein, it is possible that a sensor node could be the part of two spanning tree. In this scenario, different unique identity numbers are assigned to each SN to avoid data path loops in the network. As soon as the route construction process completes, an ACK is initiated by the leaf node, which floats over a defined route and delivered to mobile sink by the RSN in an active or proactive manner. Upon receiving an ACK message, the rules are updated in the corresponding switch table and necessary actions are performed in the network. Let the set of the sensors $S_i = \{S_1 + S_2 + \cdots + S_n\}$ and the mobile sinks $MS_i = \{MS_1 + MS_2 + \cdots + MS_n\}$ embedded with OpenFlow switches $SW_i = \{SW_1 + SW_2 + \cdots + SW_n\}$ are deployed in different regions $R_i = \{R_1 + R_2 + \cdots + R_n\}$ with their known location $L_i = \{L_1 + L_2 + \cdots + L_n\}$ for witnessing events in the SG. The sum of events data $D_i = \{D_1, D_2, + \cdots +, D_n\}$ gathered in different times $T_i = \{T_1, T_2, + \cdots +, T_n\}$ is routed over reliable links between sensors $l_i = \{l_{1(S_1,S_2)} + l_{2(S_1,S_3)} + \cdots + l_{n(S_n,S_n)}\}$ on different routing paths $R_{P(i)} = \{R_{P1} + R_{P2} + \cdots + R_{Pn}\}$ towards the selected rendezvous sensors $RS_i = \{RS_1 + RS_2 + \cdots + RS_n\}$ in the smart grid. The distance between a pair of sensors, rendezvous sensors and mobile sinks is represented by $D_{S_i,S_j} = \{D_{S_1,S_2} + D_{S_2,S_3} + \cdots + D_{S_{n-1},S_n}\}$, $D_{RS_i,RS_j} = \{D_{RS_1,RS_2} + D_{RS_2,RS_3} + \cdots + D_{RS_{n-1},RS_n}\}$ and $D_{MS_i,MS_j} = \{D_{MS_1,MS_2} + D_{MS_2,MS_3} + \cdots + D_{MS_{n-1},MS_n}\}$, respectively. In each region, the railroad path for mobile sinks for gathering data at various sojourn locations is represented by $M_{P(i)} = \{M_{P1} + M_{P2} + \cdots + M_{Pn}\}$ and $SL_i = \{SL_1 + SL_2 + \cdots + SL_n\}$ in the smart grid. Two binary variables X and $Y \in \{0, 1\}$ are used during modeling the proposed scheme as binary linear programming (BLP) in the smart grid. To this end, the main objective is to diminish the complete data collection cost in each round in the smart grid. This formally may be indicated as

$$\varphi = \sum_{i}^{n} \sum_{j}^{n} \left(\min_{D_e, B_{of}, C_{on}, C_o, E_c} S_j, B_s + \max_{R_E,\ P_{dr}, T_p} S_j, B_s \right)^{i} \tag{1}$$

$\forall i = 1, 2, \ldots, n$; $\forall j = 1, 2, \ldots, m$ and $\forall k = 1, 2, \ldots, l$;
where
D_e is the delay
T_p is the throughput
B_s is the base station
R_E is the residual energy
B_{of} is the buffer overflow
φ is the objective function
E_c is the energy consumption
P_{dr} is the packet delivery ratio
C_{on} is the network congestion
C_o is the computational and control message overhead
subject to:

$$\sum_{S_i \in MS_n} X_{S_i(L_j)}(MS_k) \geq 1 \tag{2}$$

Constraints in (2) assure that each SN deployed in a specific region is linked with a minimum one MS in the SG.

$$X_{S_i(L_J)} \leq \left(Y_{S_i(L_j)}(MS_\kappa)\right)_{R_j} = 1 \tag{3}$$

Constraints in (3) make sure that each SN deployed in a specific region is linked with one MS in the SG.

$$R_i(MS_k, S_j) \in B_s = 1 \tag{4}$$

Constraints on (4) state that each SN and MS are deployed in a specific region is linked to the BS in the SG.

$$\sum_{j=1}^{m} assign(S_i, RS_j) \geq 1, \ \forall\ S_i \in S_n \tag{5}$$

Constraints in (5) specify that every SN is linked with a minimum one rendezvous SN in the network.

$$D_{istance}(S_i, RS_j) \times A_{sign}(S_i, RS_j) \leq TR_i, \ \forall\ S_i \in S_n \text{ and } \forall\ RS_j \in RS_n \tag{6}$$

Constraints in (6) make sure that an SN that falls under the transmission range (TR_i) is assigned to the rendezvous SN in the network.

$$D_{istance}(S_i,\ S_j) \times A_{sign}(S_j,\ RS_k) \le TR_i,\ \ \forall\ S_i,\ S_j \in S_n \text{ and } \ \forall\ RS_k \in RS_l \text{ and } i \ne j \tag{7}$$

Constraints in (7) assure that all SNs that are not in the transmission range of the rendezvous SNs but are in the transmission range of other sensors that are assigned to the rendezvous SNs are also covered in the network.

$$M_{ATD} = \max\{ATD(RS_k)|1 \le k \le DT_h,\ \ RS_k \in RS_l\} \tag{8}$$

Constraints in (8) define the maximum average transmission distance (M_{ATD}) between rendezvous SNs, is greater than or equal to the defined threshold distance value (DT_h) in the network.

$$\sum_{j=1}^{m} X_{S_i,RS_j} = 1,\ \ \forall\ S_i \in S_n \tag{9}$$

Constraints in (9) state that each non-rendezvous SN must communicate with the neighboring rendezvous SNs in the network.

$$Y_{S_i} \le \sum_{S_i \in R_1} X_{Re(S_i)}\ (R_{P(k)}) \tag{10}$$

Constraints in (10) Guarantee that the number of forwarding SNs over a defined routing path is less or equal to maximum defined SNs in the SG.

$$X_{S_i(L_i)} = \ Y_{S_i(D_k)} \cdot (S_j) \le 1 \qquad \forall\ S_i,\ S_j \in S_n \tag{11}$$

Constraints in (11) verify the sum of k data packets (D_k) delivered to a SN should not be greater than its limited memory capacity in the smart grid.

$$Y_{(S_i,S_j)} l_{(S_i,S_j)} \le |R_{P(k)}|,\ \ \forall\ \ S_i,\ S_j \in P_{P(k)} \tag{12}$$

Constraints in (12) allow the flow of information over a highly stable link between SNs along a predefined data route in the SG.

$$\sum_{S_i \in (L_j)} Re_{S_i}(D_k)\ >\ \sum_{S_j \in (L_i)} S_j(L_i)(D_k) \tag{13}$$

Constraints in (13) assure that the relay SNs (Re) carry higher D_k compared to normal SNs in the SG.

$$C_r(l_k) = \sum_{\forall (S_i,\ S_j) \in R_{Pn}} SR_{P1(S_i,\ S_j)} l_k / R_{Pn} \tag{14}$$

Eq. (14) indicates the link criticality $C_r(l_k)$ over a shortest routing path (SR_{P1}) between each pair of source and destination sensors (S_i, S_j) in the network. The link criticality helps to characterize how likely a particular link with certain data rates may become a bottleneck in the network.

$$\sum_{S_j \in R_{P1}} Fl_{1(S_i,S_j)} = \sum_{S_i \in R_{P1}} Fl_{1(S_j,S_i)} \qquad S_j \ne S_i \textit{ and } S_i \ne S_j \tag{15}$$

Constraints in (15) confirm continuous flow (Fl) of information between each pair of SNs in the smart grid.

$$BS(T_i) - MS_i(T_j) - Re_{l_i(S_i,S_j)}(T_k) \le \ T_{max} \tag{16}$$

Constraints in (16) verify that the data received at the BS from MSs and SNs must not be greater than a predefined threshold time (T_{max}).

$$\sum_{SW_i \in M_{P(i)}} \left(X_{SW_i},\ Y_{RS_j|S_i}\right)^k = 1,\ \ \forall\ k \in K_n \tag{17}$$

Constraints in (17) ensure that a set of k rules is installed on each switch for collecting data from SNs and rendezvous SNs in the network.

$$I_k + \sum_{k \in K_n} \left(X_{SW_i},\ Y_{RS_j}\right)^k \le \lambda,\ \ \forall\ SW_i \in SW_n \tag{18}$$

Constraints in (18) guarantee that the initial (I_k) and the sum of k rules installed on each switch SW_i are less than or equal to a maximum defined value (λ) in the smart grid.

$$\sum_{i=1}^{n} X^{MS_k}_{RS_i.RS_p} - \sum_{j=1}^{n} Y^{MS_k}_{RS_p.RS_j} = 0,\ \ k \in MS_n,\ \ RS_p \in RS_n \setminus \{1\} \tag{19}$$

Constraints in (19) ensure that each MS visits a rendezvous SN (RS_p) in a specific region must leave that rendezvous SN in the network.

$$\sum_{l_{1(RS_i,MS_k)} \in R_i} X_{RS_i(MS_k)} = 2Y_{RS_i(MS_k)}\ \ \forall\ RS_i \in RS_n\ k = 1,\ 2,\ \cdots m \tag{20}$$

Constraints in (20) force the MSs to enter and leave the same rendezvous SN in the network.

$$\sum_{j=2}^{n} X^{MS_k}_{1.RS_j} = 1 \quad k \in MS_n \tag{21}$$

Constraints in (21) guarantee that an MS after visiting leaves the same rendezvous SNs in the network.

$$\sum_{k=1}^{l} Y_{RS_i(MS_k)} \ge 1 \quad \forall\ \ RS_i \in RS_n \setminus \{0\} \tag{22}$$

Constraints in (22) verify that the associated MS visits each rendezvous SN at least once in the network.

$$\sum_{l_{1(RS_i,MS_k)} \in R_i} X_{RS_i(MS_k)} \ge 2Y_{M_{P1}(RS_i,MS_k)}\ \ \forall\ RS_i \in RS_n,\ \ M_{P1} \in M_{Pn},\ k = 1,\ 2,\ \cdots m \tag{23}$$

Constraints in (23) impose the rendezvous SN connectivity over a predefined route followed by the MS in the smart grid.

$$RS_1^{MS_k} = 1, \quad k \in MS_n \tag{24}$$

$$RS_i^{MS_k} - RS_j^{MS_k} + 1 \le (n-1)\left(1 - X^{MS_k}_{S_i.S_j}\right),\ \ k \in MS_n\ S_i.\ S_j \in S_n \setminus \{1\} \tag{25}$$

Constraints in both (24) and (25) eliminate the sub-tours of the VRP within nodes in $S_n\backslash\{1\}$. The constraints in (24) define the value of $RS_i^{MS_k}$ for the mobile sink, i.e., $RS_1^{MS_k} = 1$, while the constraints in (25) ensure that $RS_j^{MS_k} \ge RS_i^{MS_k} + 1$, when $X^{MS_k}_{S_i.S_j} = 1$

$$D_n = \sum_{k=1}^{n} MS_k(D(S_i))^j \tag{26}$$

Constraints in Eq. (26) specify that in each round every mobile sink collects SNs information in the SG.

$$\sum_{i \in n} X_{MS_i}(D) \le C(j) \quad \forall\ \ MS_i \in MS_n \tag{27}$$

Constraints in (27) mean that every mobile sink cannot receive data higher than its defined capacity $C(j)$.

$$\sum_{i=1}^{n}\sum_{j=1}^{n} X^{MS_k}_{RS_i.RS_j}\left(T_{RS_i.RS_j} + T_{RS_i}\right) - T_1 \le D_{dl} \quad MS_k \in MS_n \tag{28}$$

Constraints in (28) defined the latency for each mobile sink. It guarantees that the travel and charge time of the MSs for one round journey such that k ($k \in MS_n$), cannot exceed the given deadline (D_{dl}) in the smart grid.

$$\sum_{i=1}^{n}\sum_{j=1}^{n} X^{MS_k}_{RS_i.RS_j}\left(T_{RS_i.RS_j} + T_{RS_i}\right) - T_1 \le \tau \quad k \in MS_n \tag{29}$$

Constraints in (29) ensure that the charging and travel time of the MSs in each subregion cannot be higher than the maximum tour time (τ).

$$\sum_{E_j \in E_n} MS_i|S_i(E_j) \le E_n \quad \forall\ S_i \in S_n \tag{30}$$

Constraints in (30) show that energy (E_j) of the SNs or MSs cannot be more than its maximum energy storage capacity E_n.

$$E_c \sum_{E_j \in E_n} MS_i | S_i(E_j) \leq RE_i \quad \forall\ S_i \in S_n \tag{31}$$

Constraints in (30) state that the energy consumption of the SNs or MSs must be low or equal to the maximum defined value in the network.

$$\begin{aligned} E_c \ = \ & E_m \sum_{i=1}^{n} \sum_{j=1}^{n} X_{RS_i.RS_j}^{MS_k} D_{S_i,S_j} + E_{rx} D_i \sum_{i=1}^{n} \sum_{j=2}^{n} X_{RS_i.RS_j}^{MS_k} \\ & + E_{tx} \sum_{i=1}^{n} \sum_{j=2}^{n} X_{RS_i.RS_j}^{MS_k} \end{aligned} \tag{32}$$

Constraints in (32) define the total energy consumption of a mobile sink, including movement energy, transmission energy and data receiving energy consumption during visiting each rendezvous SN in its one-round journey. The E_m, E_{tx} and $E_{rx}D_i$ are, the energy consumed by the mobile sink to travel one meter, the transmission energy consumption and the energy consumption receive one bit of data in the smart grid.

3.9. Dead or isolated node recovery

Throughout the data collection process, each SN periodically monitors its neighboring SNs by broadcasting a neighboring alive (NAREQ) message in the smart grid. The SNs that receive the NAREQ messages update their neighboring table and each of them replies by sending an ACK message. Upon receiving the ACK messages, the neighboring table of the sender SN is updated. However, if a sender SN did not receive an ACK message from neighboring SNs in a given time then it is supposed to be inactive. The inactive SN information is forwarded to the RSN over a predefined routing path and delivered to the MS. After matching the flows, the information is forwarded to the SDN controller. The SDN controller generates a limited broadcast instruction NAREQ message and sends it to a specific set of SNs located in a specific region near the inactive SN in the network. As soon as the information is received, the specific set of SNs starts to communicate with the inactive SN by periodically sending a predefined number of NAREQ messages. The assumed inactive SN is alive only if at least one of the neighboring SNs receives an ACK message otherwise it is declared as a dead SN in the SG. This recent information is sent to the SDN controller through an OpenFlow agent, which initiates the route construction process only if the SN was an RSN or parent SN along a predefined route in the network.

In case of an isolated SN, if a node A is interested in to send its information to node B but there is no route information exist in the routing table. Then node A sends a route request message REREQ to the SDN controller through the mobile sink, including its recent location, residual energy and unique identity in the SG. Upon receiving the RREQ message, the SDN controller computes the location of the sender neighboring SNs in the SG. As soon as the computation process finishes, the SDN controller forwards the neighboring SNs information to the isolated node in the network. Then, isolated SN based on the received information starts to communicate with the neighboring SNs by sending a REREQ message in the SG. In a case, if an isolated SN receives the RREQ messages from neighboring SNs. Then, first, it looks into its neighboring table information for each sender SN and creates a new entry only if it does not exist and saves updated information in the neighboring table. After that, it joins a neighboring SN with the maximum weight value as a leaf node and sends an ACK message to the RSN. At each hop on the defined route, new leaf node information is updated in the sensors neighboring table. If an isolated SN did not receive any RREQ reply from neighboring SNs then it uploads its sensed data through high transmission power to the closer mobile sink. All the updated information is forwarded to the SDN controller in the network. Finally, the SDN controller based on the user(s) instructions defines and updates the data flow rules in the network.

4. Path loss and energy consumption model

The path loss model numerically described in Eq. (33) is used in our simulation studies [34].

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta log_{10} \frac{d}{d_0} - X_\sigma - \ P_\eta \tag{33}$$

While the E_c model numerically described in Eqs. (34)–(36) is used in our simulation studies [35].

$$E_{T_x}(K, d) = E_{elec} \times K + E_{amp} \times K \times d^2 \ < d_0 \tag{34}$$

$$E_{T_x}(K, d) = E_{elec} \times K + E_{amp} \times K \times d^4 \ \geq d_0 \tag{35}$$

$$E_{R_x}(K) = E_{elec} \times K \tag{36}$$

in which E_{T_x}, E_{R_x}, E_{elec}, E_{amp}, K, d and d_0 are, the data packets transmitting energy consumption, the data packets receiving energy consumption, the circuitry energy consumption of receiving or transmitting data packets, the constant signal amplifier coefficient, the number of bits, the physical distance between SNs and MSs, and the threshold physical distance depends on the communication radius of the SNs in the SG. The further parameters values are given in Table 1.

5. Simulation settings and performance evaluations

We evaluate the performance of the proposed ODGRP scheme against the well known mobile sink-based data gathering protocol called the MSIEEP [30] through the discrete-event simulation tool named EstiNet9.0 [36]. In fact, the performance of both data gathering schemes is measured in the smart grid environment by using the metrics shown in Table 2.

In our simulation, we consider a 320 kV outdoor PG station with area 1200(length) × 800(width) meters containing 4 software-defined mobile sinks and 390 sensor nodes. The maximum velocity of each mobile sink is set to 2.5 m/s. A smart grid consists of systems, subsystem, and electric poles with numbers 40, 83 and 210, respectively. The initial energy of each MS and SN were set to 5 J and 12 kJ, respectively. In the SG, each sensor node is embedded with physical layer standard IEEE 802.11 g with a maximum communication range of 75 m and data rates up to 256 kbps. The maximum distance value between each mobile at any given position in a subregion to the base station was set to 1.1 km. In addition, the values of data packet size and data aggregation energy consumptions were set to 43 bytes and 0.015 W. During network operations, each sensor node observes the smart grid events and stored data in its memory of maximum size of 6 Mb. During conveying sensor data, the maximum amount of energy consumed for transmitting and receiving information between SNs is set to 0.97 W and 0.035 W in the network. In highly dynamic topologies, the values

Table 1
Simulation and path loss model parameters value and description.

Parameters definition	Values
Path loss exponent	η
Transmit power in dB	P_t
Zero-mean Gaussian variables with a standard deviation	X_σ
Noise power measured in dBm	P_η
Signal to noise ratio	γ(d)
Path loss at a reference distance d_o	PL (d_O)
Line of sight	LOS
Non-line of sight	NLOS
Path loss exponent (n) for both LOS, NLOS	2.1, 2.9
Noise floor for both LOS, NLOS	−83, −88
Shadowing deviation (σ) for both LOS, NLOS	3.01, 2.81

Table 2
Performance metrics.

Sr No.	Metrics	Definition
1	Packet delivery ratio	is the total number of data packets successfully received at the sink to the total number of data packets generated in the deployed sensor network.
2	Memory overflow	is the attempt of a sensor to store information than its maximum storage capacity.
3	Packet error rate	is the total number of corrupted data packets received at the sink to the total number of data packets generated in the deployed sensor network.
4	Throughput	is the amount of data moved between a sensor and mobile sink or pair of sensors in a certain time period measured as bits per second (bps).
5	Delay	is the time difference between a data packet sent from a sensor node to the time when it receives successfully to the mobile sink.
6	Energy consumption	is the amount of energy consumed during successfully transmitting and receiving a data packet in the network. The energy consumption is the sum of idle listening, data aggregation, packet transmission and reception in the network.
7	Network lifetime	is the time when sensors run out of energy and fail to deliver data packets to the mobile sink.

of ideal listening and sleeping power were set to 0.013 W and 3×10^{-6} W. Finally, we assumed 59 sets of simulations in order to provide consistent results in the network.

During simulations, the collected experimental results of the mobile sinks with different data gathering speeds between 0.1 m/s and 2.5 m/s are shown in Fig. 5. Fig. 5 makes it clear that with the increase in mobile sink speed from 0 m/s to 2.5 m/s decreases the data loss rates ranging from 1 to 0 representing complete and no loss cases, respectively. In ODGRP, the rate of data loss (DLR) decreases around 13% when the MS moves to gather information at the speed of 1.8 m/s in the SG. The rate of data loss rapidly decreases by 6% when the MS moves at a speed of 2.25 m/s. This data loss rate further reduces to zero when the MS moves with a speed of 2.5 m/s for gathering data in the SG. On the contrary, the data loss rate is observed close to 17.8%, 14.8% and 7%, when the mobile sink moves with the speed of 1.8 m/s, 2.25 m/s, and 2.5 m/s in the MSIEEP. The data loss rate from 1 to 0 for buffer size between 1 Mb and 5 Mb at the speed ranging from 0 m/s to 2.5 m/s is shown in Fig. 6. It makes it clear that with the increase in sensor's cache memory size the DLR significantly decreases for events monitoring applications in the network. However, the rate of decreasing data is found significant in the ODGRP compared to the MSIEEP routing mechanism in the network. In ODGRP, the data loss rate drops up to 5% with a memory size 4.2 Mb when the mobile moves to collect data at the speed of 2.2 m/s in the SG. This data loss rate further reduces to 0 with memory size 4.95 Mb when the MS moves at the speed of 2.5 m/s for gathering data in the SG. On the other hand, the data loss rate is found around 11.5%, 7.8% and 4.3% with a memory size of 4.2 Mb and 4.95 Mb and 6 Mb when the MS travels with the speed of 2.2 m/s and 2.5 m/s in the MSIEEP.

In the above-mentioned cases, it is observed that the high data rate performance is positively affected by increased mobility speeds in both the ODGRP and the MSIEEP routing schemes. The obtained simulation facts clearly show that the mobile sink realizes a success rate of delivering data around 95.5% when the mobile sink speed is around 2.2 m/s, which results in low delay and subnetwork coverage between 94.2% and 96.3% in the ODGRP. The data success rate is sharply increased to 100% with subnetwork coverage ranging from 97.6% to 100% when the MS travels at the speed of 2.5 m/s in the SG. On the contrary, the data success rate at the speed of 2.2 m/s and 2.5 m/s with converge ranging from 88% to 91.2% and 92% to 93.5% is reported between 90% and 92% in the MSIEEP in the SG. This low coverage around 92%–93% in the MSIEEP means that an average of 7.5% SNs are not visited by the mobile sinks in the SG. All these facts show that the data loss rate in the ODGRP decreases at a higher rate compared to the MSIEEP for observing events in the network. Moreover, the corrupted data packets generated in the network are shown in Fig. 7. It illustrates that the numbers of corrupted data packets in the ODGRP are around 4.3% in the initial rounds between 1 and 1500. The rate of corrupted data packets is significantly decreased up to 3.11% as the number of rounds increases between 1900 and 2800 in the SG. Finally, the rate of corrupted data packets generated in is reported around 1.98% at then ending rounds between 3500 and 4000. Similarly, the rate of corrupted data packets generated in the MSIEEP is found close to 6.7%, 5.1% and 3.9% between round numbers 1 and 1500, 1900 and 2800, and 3500 and 4000, respectively. We observe that the minimum required the speed of the MS to avoid memory overflow in a subregion increase due to longer path length caused by the high node density in the SG. In general, the least required speed of each MS for data collection in the different subregion is lower in the ODGRP in the SG. However, it is just greater than a predefined value so that the buffer overflow of the SNs located in a region can be avoided by visiting them in the SG. Therefore, in the ODGRP the data loss rate occurs due to buffer overflow is lower since data is gathered from the cache emergence SNs within a predefined amount of time in the SG. In the proposed scheme, the SNs with higher data rates are better distinguished with respect to overflow times in the SG. The proposed scheme based on its self-learning mechanism offers periodic scheduling of MSs as a function to observe the predictability of SNs, which generate information at higher frequencies in different regions in the SG. Consequently, because of the varying cycles length, the sensors in different regions have different transmission times with small variations in the SG. To this end, the MSs movement based on a self-learning mechanism further reduces the data packet loss by frequently visiting the SNs in a given time period which has smaller overflow times than other SNs in the SG.

All these facts lead to high P_{dr} in the ODGRP compared to the MSIEEP in the SG as shown in Fig. 4. It clearly shows that the data packets collected by the ODGRP are around 98% and 100% when the average spending time of the mobile sink is around 960, 1050 and 1200 s, respectively, in the network. At the same time, the data packets collected by the MSIEEP are found around 86%, 91% and 93.5% in the network. Hence, each mobile sink in the ODGRP collects more time-sensitive events data compared to the MSIEEP in the SG. This has a great impact on the ODGRP network throughput as shown in Fig. 8. It shows that the network throughput varies between SNs 1 and 390 in

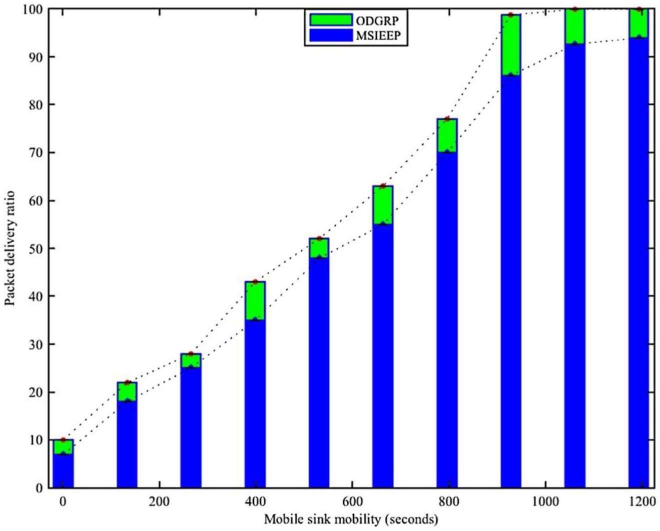


Fig. 4. Packet delivery ratio vs mobile sink visiting time in seconds.

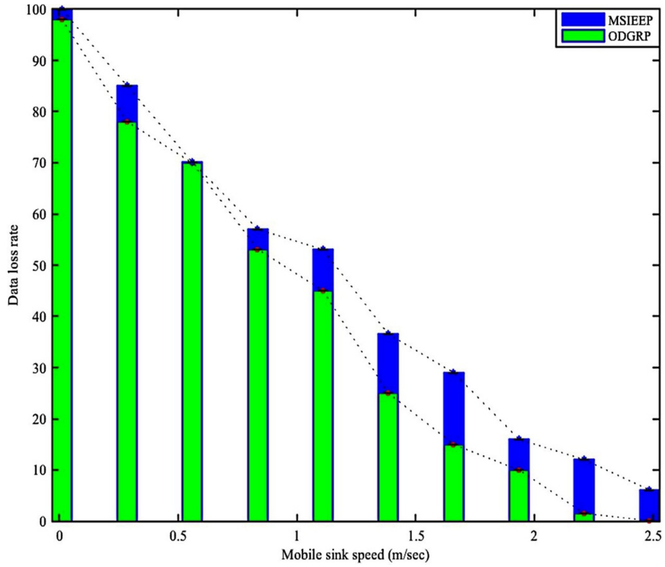


Fig. 5. Data loss rate vs mobile sink speed in seconds.

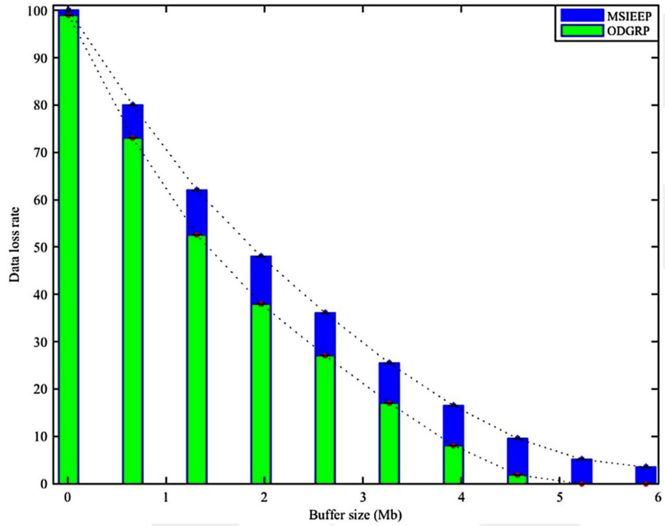


Fig. 6. Data loss rate vs node buffer size in Mb.

both the ODGRP and the MSIEEP routing schemes. However, the network throughput is observed high in the ODGRP compared to the MSIEEP in the SG. In ODGRP, the RSNs rotate periodically based on regular sink movement in the SG. On the other hand, the efficient memory utilization during monitoring events and relaying data towards the mobile sink also contribute to increase network throughput in the ODGRP as shown in Fig. 9. These facts significantly help to reduce hotspot and energy hole issues of the immediate SNs and thus more data packets are forwarded to the mobile sinks. As a result, the ODGRP performance is found better in term of network throughput as compared to the MSIEEP in the SG. One of the main issues in the MSIEEP is that, the SNs single-hop away to the mobile sink are facing issues of hotspot and energy hold due to carrying a huge amount of data coming from neighboring SNs in the SG. Therefore, in some cases, the gathered information due to these issues cannot be delivered to the mobile sinks, which degrades overall network throughput performance in the SG. Moreover, a lot of time is required by each mobile sink to cover the whole sub-network area for gathering data from SNs in the SG. This low speed than a predefined threshold value lead to sensor buffer overflows when the MS visits them in a predefined time. Hence, the DLR is higher in the MSIEEP compared to the ODGRP.

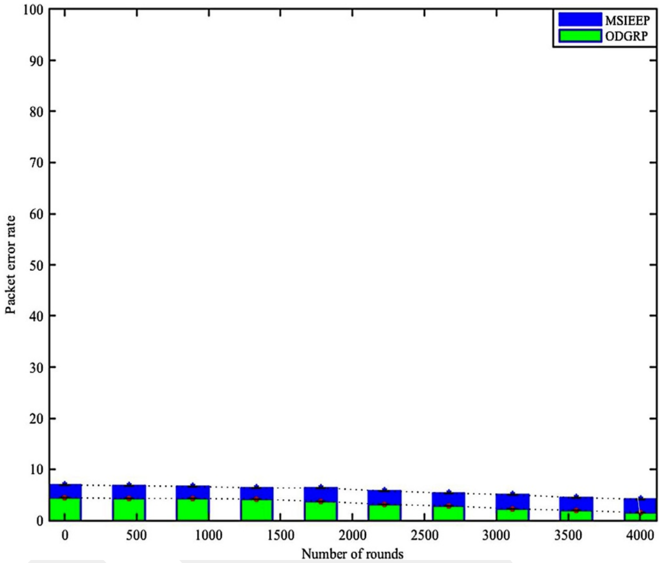


Fig. 7. Packet error rate vs number of rounds.

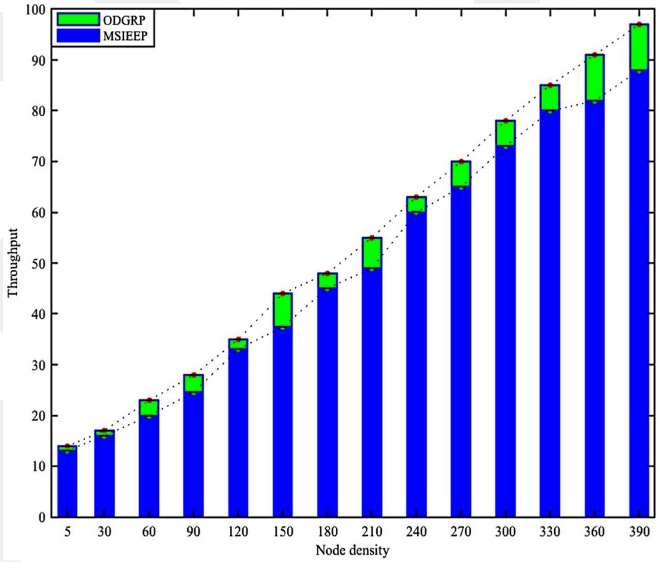


Fig. 8. Throughput vs node density.

In addition, due to lack of distinguishing SNs with respect to overflow times sacrifice performance severely in the SG. Moreover, the high speed of the mobile sinks for robust data gathering also performs poor because of not unloading the complete data from the RSNs cache during visiting them. Therefore, the overhead and redundancy in data become more with increasing mobile sink speed in the MSIEEP. As a result, its benefit of robust data gathering with low latency disappears at higher speeds for observing events data in the SG. Fig. 10 demonstrates the latency between the ODGRP and the MSIEEP data collection mechanism in the SG. In the beginning, the latency of delivering data in both routing schemes is high in the network. However, the latency values decrease as the number of rounds increases in both routing schemes. The initial data latency for monitoring events is found up to 580 ms in the ODGRP between round numbers 1 and 430 in time around 115 s in the SG. However, it decreases rapidly around 430 ms between round numbers 600 and 1500 in time around 440 s in the SG. The latency values of gathering data are noticed around 312 ms between round numbers 3300 and 4000 in time around 1000 s in the SG. On the other hand, the data latency values in the MSIEEP in the same given time are observed close to 662 ms, 583 ms and 513 ms between

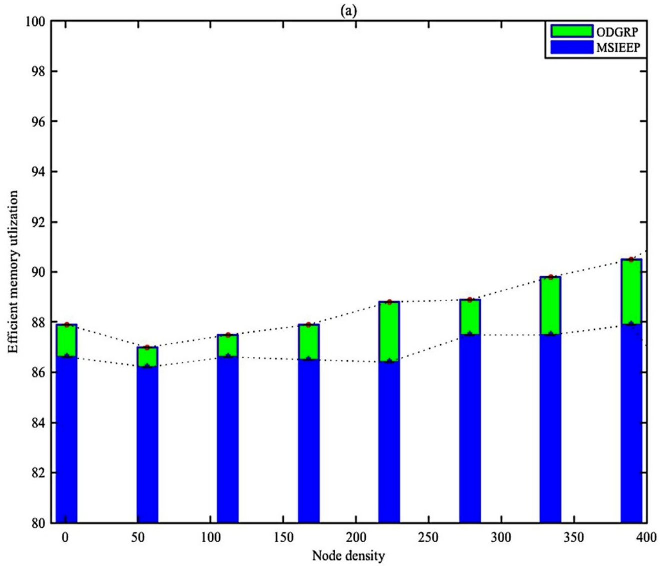


Fig. 9. Efficient memory utilization vs node density.

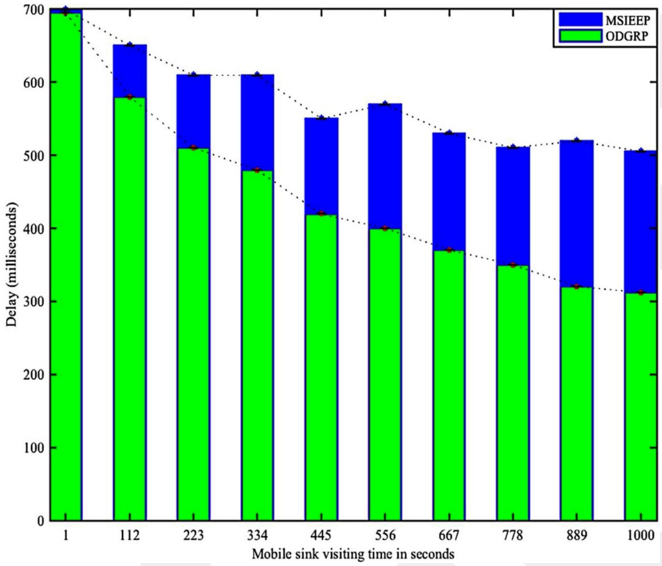


Fig. 10. Delay vs mobile sink visiting time in seconds.

round number 1 and 430, 600 and 1500, and 3300 and 4000, respectively. During simulation studies, it is noticed that partitioning the whole network into the shortest paths zones also has a great impact on the mobile sinks data gathering latency and energy consumption in the ODGRP. This significantly minimizes the round trip time of the mobile sinks over a defined route, which results in lower latency and energy consumption for gathering data in the network. This least E_c strongly impacts the lifetime of the network in the ODGRP routing scheme as shown in Fig. 11.

In addition, the software-defined mechanism significantly helps each mobile sink to gather data from SNs instantaneously in the SG. Moreover, self-learning based sink mobility pattern over a predefined route also assists to reduce data gathering latency in the network. The SDMSs by using their stored mobility history information equalize the visits and move faster in the entire regions in the SG. Consequently, each SDMS gathers time sensitive sensor data stored in their limited cache by visiting them multiple times in a given time. Generally, the SNs single-hop away to the MS directly uploads their cached information via short distance communication when it comes close enough to the RSNs. The SNs far away to the MS convey their cached data over a predefined minimum spanning routing tree in the SG. This multi-hop data forwarding over a minimum spanning tree with a restricted route length set to 5 hops towards the RSNs reduces the data delivery latency in the ODGRP in the SG. Thus, the whole cache emergence and time-sensitive data from source SNs towards the RSNs is routed over highly reliable links in the SG. This balances data traffic and network E_c load and also increases the probability of successful data delivery in the SG. Furthermore, in the case of a route failure, the SDN controller rapidly detects and reconfigures broken links in the SG. As a result, it significantly reduces the energy consumption of sensors by reducing network control message overheads and thus increases the NLT of the ODGRP in the SG.

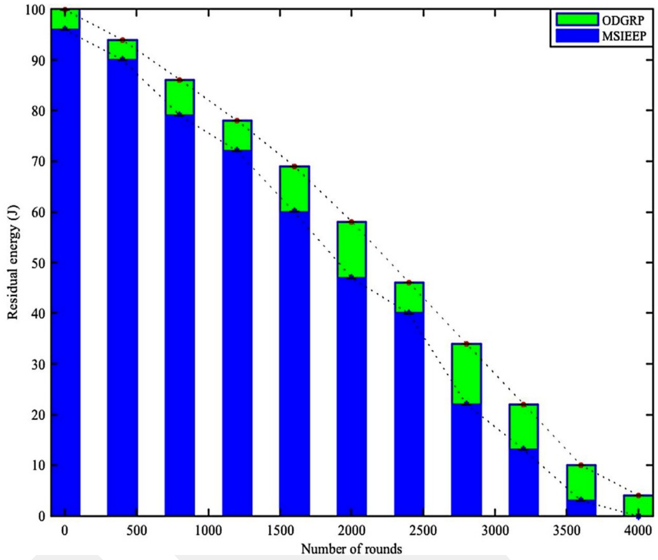


Fig. 11. Residual energy vs number of rounds.

On the contrary, this is not the case in the MSIEEP. The mobile sinks in the MSIEEP are facing longer delays because of partial network coverage that avoids some areas as outside of service where a number of SNs reside in the SG. Thus, any mobile sink does not frequently visit these areas for gathering data in the SG. The other main reason is an increasing number of data forwarding SNs with a small transmission range from the source towards the mobile sink. This may help to balance the network energy consumption but it consumes a notable amount of SNs energy in the network. Moreover, it also increases the probability of high latency because of path loops, corrupted data packets and uneven E_c in the SG. In the MSIEEP, the other reason for high data gathering latency is because of its instant route failure and bottlenecks appears due to carrying a huge amount of neighboring data in the SG. In most of the scenarios, it fails to find alternative paths instantaneously, which result in loss of data due to not reaching at the mobile sink in a predefined time. As a result, the data success rate slightly drops in the MSIEEP. Finally, during finding new routes for data transmission also require a large number of communication overheads, which consume SNs energy and thus the NLT decreases rapidly in the MSIEEP. In sum, compared to the MSIEEP, the ODGRP scheme is extremely suitable for observing smart grid events and thus provide power supply in an efficient, sustainable and economical manner with minimal impact on the environment in the smart cities.

6. Conclusions and future work

The smart city concept has drawn considerable worldwide attention and has the potential to provide sustainable and economical services to their citizens for a better quality of life. The major area of concern in smart cities is to provide continuous and quality-aware power supply to buildings, factories, transport sector, etc., to perform routine activities.

In this context, the smart grid is a vital intelligent technology that can provide energy in a more efficient, effective, sustainable and economical manner. However, real-time monitoring and control of the smart grid for continuous and quality-aware energy supply in the smart cities is challenging and requires an advanced QoS-aware communication framework. In this context, this study presented a novel opportunistic data gathering using the Internet of software-defined mobile sinks and WSNs in the smart grid. The extensive simulations performed through the EstiNet9.0 show that the proposed ODGRP scheme is efficient for QoS-aware data collection compared to existing routing solutions in the SG. As a future work, the researchers are interested in designing a novel mobility mechanism to minimize location updating overhead between MSs and the RSNs in the SG.

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Conflict of interest

Authors declare that there is no conflict of interest.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.csi.2019.03.009.

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